INTERNAL-COMBUSTION ENGINES

THEIR PRINCIPLES AND APPLICATION TO AUTOMOBILE, AIRCRAFT, AND MARINE PURPOSES

BY

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PREFACE

The purpose of this book is to provide a practical and up-to-date text on the subject of Internal-Combustion Engines. The endeavor has been to arrange and present the subject matter in such a manner as to bring it well within the comprehension of the average student. For more advanced students, who have a knowledge of thermodynamics, the writer has presented in Chapter III the theoretical considerations of the various cycles which are applicable to internal-combustion engines. No attempt has been made to treat the problems of actual design, these problems being fully covered in many excellent books on this particular subject.

The author is indebted to the following for many of the illustrations and other material he has used in the preparation of this book: American Bosch Magneto Corporation; Bureau of Steam Engineering, Navy Department; Continental Motors Corporation; Crosby Steam Gage and Valve Company; Dayton Engineering Laboratories Company; Detroit Lubricator Company; D. Van Nostrand Company; Franklin Automobile Company; Hall-Scott Motor Car Company; Packard Motor Company; Splitdorf Electrical Company; Standard Motor Construction Company; Stromberg Motor Devices Company; Tide Water Oil Company; Van Blerck Motor Company; Wheeler-Schebler Carburetor Company; Wireless Press, publishers of "Practical Aviation"; Wright-Martin Aircraft Corporation; Zenith Carburetor Company.

In conclusion the author desires to take this opportunity of expressing his thanks to Lieutenant-Commander J. J. Broshek, United States Navy, for his many helpful criticisms and valuable suggestions during the preparation of the manuscript.

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INTERNAL-COMBUSTION ENGINES

CHAPTER I

HISTORICAL SKETCH

There is but little information available as to the origin of the internal-combustion engine. In 1680 Huygens, a Dutchman, proposed to use gunpowder for the purpose of obtaining motive power. A small quantity of gunpowder, exploded in a large cylindrical vessel filled with air, expelled the air through check valves, thus leaving, after cooling, a partial vacuum. The pressure of the atmosphere then drove a piston down to the bottom of the vessel, lifting a weight or doing other work.

The Abbé Hautefeuille advanced similar ideas but does not seem to have made actual experiments. These early engines cannot be classed as gas engines. Papin, in 1688, stated that the experiments along this line were unsuccessful, so devoted his attention to steam. About one hundred years later (in 1794) Robert Street, an Englishman, patented the first real engine. It contained a motor cylinder in which worked a piston connected to a lever. This lever operated a pump. The bottom of the motor cylinder was heated by fire. A few drops of turpentine were introduced and evaporated by the heat. The piston was then drawn up, admitting a quantity of air, which mixed with the inflammable vapor. Ignition was secured by drawing in a flame through a port uncovered by the piston. The resulting explosion drove the piston up to the end of its stroke and forced the pump piston down, so performing work in raising water. The details of this engine were crude, but the main idea was correct.

In 1799 Lebon, a Frenchman, patented a gas engine in which gas and air were supplied from separate compressing pumps to a combustion chamber where the mixture was detonated. The hot gases were then distributed by means of valves to a motor cylinder. Both motor and pump cylinders were double-acting. The engine resembled what became known later as a constant-pressure engine. The inventor's notions were vague, however, for he does not distinguish very clearly between explosions and constant pressure. Lebon had but little time to continue his experiments or to develop his ideas, for he was assassinated in 1804.

In 1820 the Reverend W. Cecil of Cambridge, England, described an engine which was moved by pressure of the atmosphere upon a vacuum caused by the explosion of hydrogen gas mixed with air. In his paper he described an engine which he had constructed to operate according to the explosion-vacuum method. He stated that at sixty revolutions per minute the explosions took place with perfect regularity. This paper gives an account of the first gas engine which appears to have been worked in England, and, it is believed, in the world.

In 1838 William Barnett, an Englishman, invented the compression system now so largely used in gas engines. It is true that Lebon described an engine using compression in 1799, but his cycle in no way resembles that proposed by Barnett, nor is it used in the modern engine. Barnett describes three engines, the first is single-acting, the second and third are double-acting. All these engines compress the explosive mixture before igniting it. In the first and second engines the gas and air are compressed by pumps into receivers separate from the motor cylinder, but communicating with it by a short port which is controlled by a piston valve. The piston valve also serves to open communication between the cylinder and the air when the motor piston discharges the exhaust gases. In the third engine the explosive mixture is introduced into the motor cylinder by pumps, displacing, as it enters, the exhaust gases resulting from the previous explosion. The motor [illegible] by its ascent and

descent compresses the mixture. Part of the compression is accomplished by the charging pumps, but it is always completed in the motor cylinder itself.

In all three engines the ignition takes place when the crank is crossing the dead center, so that the piston gets the impulse during the whole forward stroke. The flame method of ignition invented by Barnett was very efficient. It was widely used until about 1892.

Previous to 1860 the gas engine was in the experimental stage. Many attempts were made to improve it, but none of the inventors sufficiently overcame the practical difficulties to make their engines a commercial success.

Lenoir, a Frenchman, occupies the position of inventor of the first gas engine that was actually introduced regularly to public use. This engine was first constructed in Paris in 1860. It was built along the lines of a double-acting steam engine. The ignition was obtained by means of a primary battery and coil producing a jump spark. Altogether the engine was a very decided advance over all existing forms of gas engines up to that time. The motion of the engine was as smooth and silent as that of the best steam engine. No shock whatever was heard from the explosion. The engine, however, was very uneconomical, and the great heat required that the piston be flooded with oil. For these reasons the Lenoir engine soon disappeared. The real reasons for the uneconomical working of this engine were lack of compression, incomplete expansion, and heat loss through the walls.

In the year 1862 M. Beau de Rochas, a French engineer, took out a patent setting forth, theoretically, the best working conditions for an internal-combustion engine, with a view to utilizing more completely the heat supplied. His cycle of operations was in all respects the same as that in use at the present day in the so-called Otto cycle engines. The following four propositions were embodied in his patents:

1. The largest cylinder capacity with the smallest possible cooling surface.

2. Maximum possible piston speed.

3. The greatest possible pressure at the beginning of the working stroke.

4. The greatest possible expansion.

To obtain the results which he laid down as being necessary for high efficiency, Beau de Rochas proposed to use a single cylinder and to carry out the cycle in four strokes as follows:

1. Drawing in the charge of gas and air on the first, or suction, stroke.

2. Compression during the following stroke.

3. Ignition at the dead point and expansion during the third stroke.

4. Forcing out the burned gases from the cylinder on the fourth and last, or return, stroke.

At the Paris Exposition of 1878 Otto and Langen, two Germans, brought out the celebrated Otto engine, which almost immediately superseded all other motors and created a revolution in the construction of gas engines. In this engine the whole cycle of Beau de Rochas was carried out in one cylinder. The four cycles were divided into four piston strokes covering two revolutions, thus obtaining one working stroke for each two revolutions in a single-cylinder single-acting engine. This engine has become the standard type of internal-combustion engine.

In 1879 a modification of this engine was produced by Dugald Clerk, an English engineer. In the Clerk engine the charge was compressed and exploded once every revolution, as against one explosion every two revolutions in the engines of the Otto type. The Clerk engine is known as the two-cycle type.

In 1873, before Otto took out his patents, George B. Brayton, an American, took out patents for a gas and an oil engine. In both these engines combustion took place at constant pressure. The gas engine was never successful, so oil was resorted to as fuel. This engine was mechanically better than any previous design of internal-combustion engines, but its economy was insufficient to enable it to compete with other types.

In 1893 a new form of internal-combustion engine was described by Rudolph Diesel, a German scientist and inventor. This engine does away with many of the difficulties of the gas and oil engines, and at the same time gives a much higher efficiency. The essential feature of his engine consists in the compression of atmospheric air to a sufficient temperature to ignite the fuel, which is injected at a predetermined rate during a part of the expansion, or working stroke. The oil used as fuel is injected in the form of a spray by air that is compressed separately in a compressor under a pressure 300 or 400 pounds above that in the main cylinder. The engines have this advantage: the work can be regulated by the amount of fuel supplied. This amount is not controlled, as in explosive engines, by the necessity of forming an explosive mixture. The cycle has a resemblance to that of the Otto engine, but differs from it in that the air only is compressed in the main cylinder, and the combustion is not accompanied by an explosion. This type of engine, or modifications of it, is used in practically all submarines.

CHAPTER II

ELEMENTARY CONSIDERATIONS

There are three important sources of energy available for industrial uses. The first of these is the muscular power of man and animals. The second of these sources of energy is that due to the position or motion of a body whereby it possesses potential or kinetic energy. The third is the energy which is manifested by the chemical reactions that occur in combustion or oxidation. The most important manifestation of this third group is heat, and it is in the conversion of this heat into mechanical energy that we are now interested.

The heat energy released by the combustion of fuel is converted into mechanical energy by means of an engine. If a steam engine is used, an intermediate member is needed, this member being the boiler. The chemical energy of the fuel is changed into heat energy in the furnace, and this heat energy is transferred to the water in the boiler. The water in this case acts as the carrier of the heat. Other heat carriers could be used in place of water, but water is plentiful and possesses characteristics which make its use for this purpose most desirable. The water being changed into steam in the boiler, the heat in this steam is converted into mechanical energy by forcing a piston back and forth in a steam-engine cylinder.

In the internal-combustion engine, combustion takes place in the cylinder itself, which thus acts as the furnace of the boiler. The heat carrier, or medium, in this case is the air required for the combustion of the fuel. The mechanical action of the internal-combustion engine is similar to that of the steam engine, differing principally in that most engines of the former type are single acting and hence require no piston rod or crosshead and the cylinder need be closed at one end only.

Comparison of the Efficiency of the Internal-Combustion Engine and the Steam Engine

An ideal cycle of operations was stated and first explained in 1824 by Carnot, a French engineer. This gave engineers the first theoretical basis for comparing any heat engine with an ideally perfect engine. The efficiency of the Carnot cycle, the highest attainable,[1] is $\frac{T_1 - T_2}{T_1}$, where T_1 is the maximum absolute temperature reached in the cycle, and T_2 is the minimum absolute temperature. The range of temperature for the cycle is, therefore, between T_1 and T_2. The value of T_2 is fixed by the atmospheric temperature and is the same for either the internal-combustion engine or the steam engine, assuming both these engines to operate on the Carnot cycle. In the steam engine a generous value of T_1 would be about 960° for 250 pounds steam pressure and 100° of superheat. With a value of T_2 at 70° F., or 530° absolute, the efficiency would be .45. With a temperature of 3460° absolute in the cylinder of the internal-combustion engine, the efficiency would be .85, or nearly twice that of the steam engine. The internal-combustion engine, then, has an apparent advantage over the steam engine in the ratio of .85 to .45. The considerations shown below greatly alter these values.

Comparison of Heat Losses

In the steam engine part of the steam is condensed during the expansion within the cylinder. To reduce this loss it is necessary to fit steam jackets to supply heat to the steam in the cylinders.

The greater part of the heat that is transferred from the boiler furnace to the water in the boiler goes into the latent heat or heat of evaporation. At the exhaust pressure of the steam engine this heat is no longer available for doing work but is lost to the circulating water in the condenser.

[1] It can be shown that no heat engines can be more efficient than a Carnot engine operating over the same temperature range.

In the internal-combustion engine the opposite is true, and instead of retaining all the heat of combustion in the cylinder some of it must be removed, because the temperatures attained are high enough to injure the cylinder and valves. This excess heat is usually carried off by circulating water through a jacket, called the water jacket, surrounding the working cylinder.

The effect of the combustion of the fuel within the cylinder of the internal-combustion engine is to raise the pressure as well as the temperature of the gases. The expansion of these gases in the cylinder reduces both temperature and pressure; but as it is neither practicable nor possible to expand the gases to the temperature of the atmosphere, we have here another large loss which materially decreases the theoretical efficiency of the cycle.

Sources of Heat Energy used

Different combustible gases with varying calorific values form the source of heat energy and power of the internal-combustion engine. The gas is ignited within the cylinder itself. The effects obtained by ignition and burning cannot be determined nor understood without a knowledge of the chemical constituents of the fuel and the proportions in which they combine with the oxygen of the air. The fuel does not contain the oxygen necessary for its combustion, so must be mixed with a certain proportion of air. In order to determine the temperatures and pressures in the cylinder, and to calculate the work per cycle which a certain amount of fuel will give, it is necessary to know the composition and heat value of a pound of the fuel used and the proportion of air added.

Parts of the Internal-Combustion Engine and their Functions

The function of the mechanism of any engine is to provide a means whereby the heat energy of the fuel can be efficiently converted into useful mechanical work. A study of its construction and parts is needed in order to become familiar with

the engine as a whole and with the terms used in describing it. Some of the principal parts are described below.

The *cylinder* is usually made of hard, close-grained cast iron and may be arranged either horizontally, vertically, or at an angle to the vertical, according to the type of engine. In most aircraft engines the cylinders are made of steel.

For reasons already given, the cylinders must be provided with some means of cooling the walls. In small engines this may be accomplished by placing fins, or ribs, on the outer surface of the cylinder to expose a large cooling area to the outside air. The largest engines and the majority of smaller ones are water cooled, the cylinders being cast with outer walls, or jackets, inside of which water is circulated to cool the inner wall.

Pistons are usually made of a good grade of close-grained cast iron or aluminum alloy. In larger engines, cast steel is sometimes used. The pistons are similar to the steam-engine pistons except that they are longer. For single-acting engines the trunk piston is the type generally employed. Usually no special provision is made for the cooling of this type of piston, as the circulation of air within it is sufficient. All pistons are provided with rings to prevent leakage between the piston and the cylinder walls.

The *valves* of an internal-combustion engine serve the same purpose as the valves of a steam engine. They admit the fresh mixture of air and fuel into the cylinder at the proper time and permit the exhaust gases to escape. In some engines slide valves are used to perform these functions, but poppet, or lift, valves are most commonly used. Valves for small cylinders are made of alloy steel. The valves are worked from an auxiliary, or cam, shaft. In most engines the valves are actuated by cams, while in large engines eccentrics are generally employed.

The force on the piston of the internal-combustion engine is transmitted to the revolving crankshaft through a connecting rod and crank in the same manner as in the steam engine. In single-acting engines there is no piston rod, but the connecting rod is fastened directly to the trunk piston, which also acts as

a crosshead. In double-acting engines the arrangement is the same as that of the steam engine, there being a piston rod, crosshead, and connecting rod. These parts are usually made of open-hearth steel.

To reduce cyclic variations in speed a flywheel is used. This is commonly made of cast iron. For high-speed automobiles and motor boats a steel disk is generally used.

Processes required for a Complete Cycle

In all internal-combustion engines the following six processes are required for a complete cycle: (1) suction stroke and admission of the charge; (2) compression; (3) ignition of the compressed mixture; (4) combustion or explosion; (5) expansion of the products of combustion; (6) exhaust.

1. In most modern engines the charge of gas and air is admitted to the cylinder through ordinary poppet valves. Before entering the cylinder the gas passes through a carburetor, where it is supplied with the proper porportion of air. In oil engines the fuel and air are admitted separately.

2. After the charge of air and gas has been drawn into the cylinder, this charge is compressed into the combustion space. The efficiency and power of the engine increases with the increase of compression; compression also makes the combustion more certain and rapid, and permits the use of lean gases, which would otherwise be difficult to ignite. The upper limit of compression is set by the ignition temperature of the mixture used.

3. In order that the compressed charge may burn and do work upon the piston, it must be ignited. There are several ways of accomplishing this, but the following are the most generally used: hot tube, combustion due to high compression temperatures, and the electric spark. The two forms of electric ignition most commonly used are the generator battery and the magneto system. Ignition by high-compression temperatures is used in high-pressure oil (Diesel) engines. The hot-tube ignition is met with in older types of engines. The tube is closed at

its inner end and is heated by an external flame. At the proper time communication is made with the compressed gases, which are then ignited by the tube.

4. Combustion takes place in the combustion, or clearance, space of the cylinder as ignition occurs. The amount of compression determines the relative volume of this combustion space. The point of ignition is usually at or near the dead center; that is, when the piston is at or near the end of the compression stroke.

5 and 6. Expansion of the products of combustion is carried to the end, or nearly to the end, of the working stroke, according to the type of engine used. The burned gases should then be expelled as quickly and completely as possible. The exhaust valve opens when both temperature and pressure are still high, and on this account the heat losses in the exhaust are considerable.

Lubrication

Interior lubrication is of great importance in an internal-combustion engine. In the steam engine this problem is not very difficult, on account of the lower temperatures used and the presence of a water vapor in the cylinders. In the internal-combustion engine the interior working surfaces are dry and the temperatures and pressures both high. For this reason the lubrication of the piston and cylinder walls requires great care and the selection of proper lubricating oils.

Regulation of Speed and Power

The methods adopted for regulating the speed or power of internal-combustion engines may be classified under five heads: (1) by regulating the proportion of air and fuel; (2) by regulating the amount of air and fuel without changing the proportion; (3) by omitting the supply of fuel during a part of the cycles; (4) by varying the time of ignition; and (5) by combination of (2) and (4).

Starting Devices

Since an internal-combustion engine must do the work of drawing in and compressing its charge before energy is developed in the cylinder, some special device is required to start such an engine. This involves the use of power from an external source. It is seldom, if ever, convenient to apply power sufficient to start such an engine under its load, and consequently there must be some gear to disengage the load.

A small engine can be started by hand, by turning the flywheel or by a special hand gear. The latter should have a ratchet, or clutch, which will release or throw it out of gear as soon as power is developed. Hand power is then applied until the operations of charging, compressing, and igniting are performed, whereupon the engine should start promptly. When the engine is started in this manner, the ignition should be delayed until the piston is past the dead center; otherwise it is likely to start backwards and cause an accident.

When electric or other external power can be substituted for hand power, this method may be used for starting engines of large size. Very large engines are usually started by compressed air, in the same way that steam is used in a steam engine.

CHAPTER III

THE THERMAL PROPERTIES OF GASES, AND THE PRINCIPAL IDEAL CYCLES APPLICABLE TO INTERNAL-COMBUSTION ENGINES

In a study of the various phenomena and changes which occur within the cylinder of an internal-combustion engine it is necessary to understand the laws of physics underlying the behavior of the working substance, which in the present instance is considered as a gas.

The physical state of a gas from a thermodynamical point of view is defined by its pressure, temperature, and volume, for with a knowledge of these three factors all the other properties can be found.

It will be necessary, before dealing with these properties and with the laws concerned, to define the units employed, commencing with the unit associated with temperature.

The *unit of heat*, which is used for expressing quantities of heat, is the British thermal unit (B. T. U.), and is defined as the amount of heat required to raise the temperature of one pound of water 1° F. As this quantity varies slightly with the temperature of the water, it is usual to specify 62° F. as the standard temperature.

The *unit of work* is the *foot pound*; that is, the work done by a force of one pound acting through a distance of one foot.

As heat is convertible into mechanical work, it is necessary to know the relation between the two respective units. The relation now adopted as correct is that one B. T. U. of heat is equivalent to 778 foot pounds of work. This quantity is usually known as the *mechanical equivalent of heat*.

The two principal laws governing the expansion and compression of gases are known as Boyle's law and Charles's law. These laws are stated and explained below.

Boyle's Law

Boyle's law states that for a given mass of gas, at constant temperature, the pressure varies inversely as the volume. Using the letters P and V to represent pressure and volume respectively, we have P varies as $\frac{1}{V}$; that is,

$$P \times V = \text{constant.} \tag{1}$$

Charles's Law

Clarles's law states that when a given mass of gas expands under constant pressure, equal increments of temperature produce equal increments of volume. This law also states that all gases expand alike.

By a combination of these two laws we deduce the general characteristic equation for gases,

$$PV = RT, \tag{2}$$

in which P is the absolute pressure in pounds per square foot; V is the volume of the gas in cubic feet; T is the absolute temperature of the gas on the Fahrenheit scale, found by adding 459.6° to the Fahrenheit temperature of the gas; and R is a constant depending upon the density of the gas.

Since the mass of a quantity of gas at a given pressure and temperature is proportional to its volume, it follows that the equation combining the pressure, temperature, volume, and mass of a quantity of gas may be written

$$PV = wRT, \tag{3}$$

where w is the weight in pounds of the quantity of gas considered. Any gas whose properties are such as to fulfill exactly the relation given above, at all temperatures and pressures, is called a *perfect gas.*

If a quantity of gas suffers a change of state and, as a result, assumes the pressure P_1, a volume V_1, and a temperature T_1, we may, of course, write

$$P_1V_1 = wRT_1. \tag{4}$$

Combining equations (3) and (4), we have

$$\frac{P_1 V_1}{T_1} = \frac{PV}{T}, \tag{5}$$

which is another form of the characteristic equation. This equation is oftener more convenient than equation (3).

The value of R in the characteristic equation may be found as follows:

$$R = \frac{PV}{T} \quad \text{when} \quad w = 1 \text{ lb.}$$

Substituting the known values for air at standard conditions of pressure and temperature, we have

$$R = \frac{2116.32}{0.08071 \times 491.6} = 53.34.$$

2116.32 = pressure of the atmosphere per square foot, with the barometer at 29.92 inches of mercury.

$$V = \frac{1 \text{ lb.}}{\text{weight of 1 cu. ft. of air}} = \frac{1}{0.08071}.$$

$$T = 32° + 459.6° = 491.6° \text{ F.}$$

The value of R for any other gas may be found by using the weight per cubic foot of that gas in place of 0.08071. Thus, for hydrogen

$$R = \frac{2116.32}{0.00559 \times 491.6} = 767.37.$$

The value of R for a mixture of gases may be found by multiplying the fractional weight of each constituent by the value of R for that gas and by adding the products. Thus, for a producer gas with the following composition by weight

$$\begin{aligned} H_2 &= 0.05\% \\ CO &= 23.00\% \\ CH_4 &= 1.50\% \\ CO_2 &= 10.45\% \\ N_2 &= \underline{65.00\%} \\ & 100.00\% \end{aligned}$$

we have

$$\begin{aligned} .0005 \times 767.37 &= .384 \\ .230 \times 53.726 &= 12.357 \\ .015 \times 110.719 &= 1.660 \\ .1045 \times 36.31 &= 3.749 \\ .650 \times 54.737 &= \underline{35.579} \\ & 53.729 \end{aligned}$$

Therefore R of the mixture is 53.729.

The application of the general equation $PV = wRT$ may best be shown by an example. What will be the size of a tank required to hold 1000 pounds of the gas mentioned above when the temperature is 70° and the gauge pressure one-half pound per square inch?

$$V = \frac{wRT}{P}.$$

$$P = 2116.32 + \tfrac{1}{2} \times 144 = 2188.32.$$

$$w = 1000.$$

$$R = 53.729.$$

$$T = 459.6 + 70 = 529.6.$$

$$V = \frac{1000 \times 53.729 \times 529.6}{2188.32} = 13{,}000 \text{ cu. ft.}$$

Specific Heats of Gases

In general the heat required to raise the temperature of a unit weight of substance one degree under given conditions is called the specific heat of the substance.

We may have two conditions under which a mass of gas may be heated. It may be confined within a definite space and heated at constant volume, or it may be confined under a definite pressure and allowed to expand as it is heated. In the case of the gas confined at constant volume the increase of pressure resulting from the addition of heat does not, of course, perform work. When, however, the gas is confined at constant pressure and allowed to expand as it is heated, work is performed. It is found that the amount of heat required to raise

one pound of gas one degree in temperature differs under these two circumstances, being greater when the gas is heated at constant pressure than when it is heated at constant volume. Experiments show that the excess of heat required in the former case is equal to the amount of work done by the gas in expanding at constant pressure.

The specific heat of a gas at constant pressure is the number of B.T.U.'s required to raise the temperature of one pound of it one degree F. at any constant pressure. The symbol for this is C_p.

The specific heat of a gas at constant volume is the number of B.T.U.'s required to raise the temperature of one pound of the gas one degree F. at constant volume. The symbol for this is C_v.

The Expansion of Gases

A gas may expand or contract in two principal ways:

1. It may expand or contract at constant temperature; that is, isothermally.

2. It may expand or contract so that it neither receives nor loses heat in any manner; that is, adiabatically.

When a gas expands isothermally, it follows Boyle's law according to the equation $PV = RT$. When adiabatic expansion occurs, the work which the gas does in expansion is done at the expense of its internal energy, no heat being exchanged between the gas and outside sources by the usual processes of radiation and conduction.

In actual internal-combustion engines the compression and expansion of the gases occupy only a very small period of time, so that the gases themselves have very little opportunity for losing or gaining heat, and hence the performances are sensibly adiabatic. Experience has shown that an adiabatic expansion takes place according to the exponential equation $PV^n = P_1V_1^n$, in which n has a value between unity and 1.40. The value of the exponent n depends upon the ratio of the specific heats. For a perfect gas it is equal to $\frac{C_p}{C_v}$.

The values of n, C_p, C_v, R, etc. for various substances may be found in Table I at the end of this chapter.

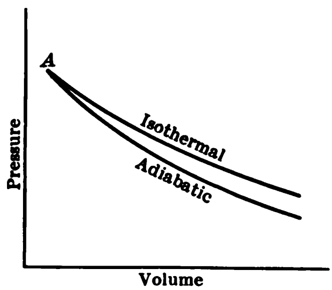


FIG. 1. Isothermal and adiabatic lines

It is frequently necessary to consider cycles of operation in which both isothermal and adiabatic changes are involved; so it will be of value to compare the two changes graphically, as shown in Fig. 1. It will be seen that if a gas originally defined by the coördinates of the point A be expanded respectively in the above two manners, the adiabatic method gives a more rapid rate of decrease of pressure. Conversely, if a given volume of gas be compressed adiabatically and isothermally, it will attain a higher final pressure in the former case, the final volume being the same.

THE WORK DONE IN EXPANSION

1. *Isothermal expansion* ($n = 1$). In an isothermal expansion,

$$\text{Work done} = P_1 V_1 \log_e r, \tag{6}$$

where r is the ratio of expansion $\frac{V_2}{V_1}$.

Also, $$\text{Work done} = RT \log_e r, \tag{7}$$

expressed in terms of the constant temperature T.

2. *Adiabatic expansion according to PV^n = constant.* Supposing the expansion occurs according to the law PV^n = constant, the work done is given by

$$\frac{P_1 V_1}{n-1}\left[1 - \left(\frac{V_1}{V_2}\right)^{n-1}\right]; \tag{8}$$

or, $$\text{Work done} = \frac{P_2 V_2}{n-1}\left[\left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}} - 1\right]. \tag{9}$$

Also, $$\text{Work done} = \frac{P_1V_1 - P_2V_2}{n-1}; \tag{10}$$

and, since $$P_1V_1^n = P_2V_2^n,$$

$$\text{Work done} = \frac{R(T_1 - T_2)}{n-1} \tag{11}$$

in terms of the initial and final temperatures.

EXAMPLE. A pound of air at 32° F. and under atmospheric pressure is compressed to a pressure five times the original. What will be the final volume and work done in an isothermal compression ($n = 1$) and in an adiabatic compression where $n = 1.4$? The volume of one pound of air at 32° F. and one atmosphere is 12.4 cubic feet approximately.

For isothermal compression,

$$\frac{P_1}{P_2} = 5,$$

$$V_2 = 12.4 \text{ cu. ft.},$$

$$\frac{V_2}{V_1} = \frac{P_1}{P_2} = \frac{12.4}{V_1} = 5 \text{ cu. ft.};$$

whence $$V_1 = 2.48 \text{ cu. ft.}$$

$$\text{Work} = P_2V_2 \log_e \frac{P_1}{P_2} = 2116 \times 12.4 \log_e 5;$$

$$= 2116 \times 12.4 \times 1.61 = 42{,}300 \text{ ft. lb.}$$

For adiabatic compression,

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{1.4}} = \frac{12.4}{V_1} = 5^{\frac{1}{1.4}} = 5^{.71}.$$

5 may be raised to the .71 power by means of logarithms as follows: $5^{.71}$ is equal to the number whose logarithm is .71 log 5. Log 5 = .699, .71 × .699 = .4963, and the number of which this is the logarithm is 3.13. Hence

$$V_1 = V_2 \div 3.13, \quad \text{or} \quad 1 \qquad 3.96;$$

$$\text{Work} = \frac{P_2V_2}{n-1}\left[\left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}} - 1\right] = 21 \qquad \left[5^{\frac{.4}{1.4}} - 1\right]$$

$$= \frac{2116 \times 12.4}{.4} \times 583 = 3$$

Entropy

Mechanical work may be represented by the area under a curve. It is desirable to be able to represent heat in a similar manner. If absolute temperature is chosen as one coördinate of the diagram, the other must be the heat added per degree of absolute temperature. This expression, which is a purely abstract quantity having no physical existence, is called *entropy*. The symbol used to represent it is ϕ. It is found by dividing the total heat of the substance by its absolute temperature. Expressing it algebraically, we have

$$\phi = \frac{Q}{T}, \tag{12}$$

where Q is the total heat of the substance expressed in B.T.U.'s.

We are never concerned with the absolute value of the entropy of a system in a given condition. What is desired is

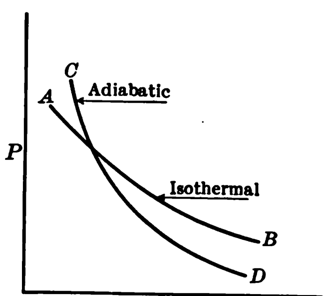


Fig. 2. The PV plane

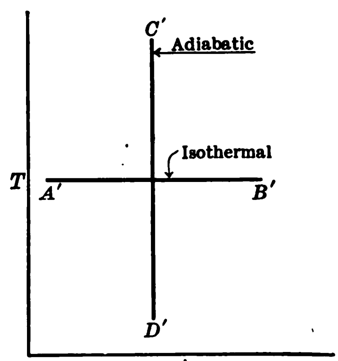


Fig. 3. The $T\phi$ plane.

the change of entropy corresponding to a given change of condition. For convenience of calculation we may assume the zero of entropy to be the entropy of the system in some specified state.

It is sometimes useful and convenient to represent isothermal and adiabatic changes, not upon the pressure-volume diagram but upon the temperature-entropy diagram. For pressure-volume changes the PV diagram is more convenient.

On the $T\phi$ diagram the entropy is constant during an adiabatic change. The difference between the PV plane and the $T\phi$ plane is shown in Figs. 2 and 3.

Consider an isothermal line AB on the PV diagram; this will be represented on the $T\phi$ diagram by the line $A'B'$, at a temperature T, parallel to the ϕ axis.

Also, an adiabatic curve CD will be represented on the $T\phi$ diagram by a straight line $C'D'$ parallel to the T axis and at a distance from it equal to the constant entropy of the adiabatic CD.

By the same reasoning, straight lines on the PV diagram would become curved lines if transferred to a $T\phi$ diagram.

Ideal Cycles Applicable to Internal-Combustion Engines

For the purpose of comparing the actual working of any engine with that of other engines, it is necessary to have some ideal standard of comparison. In steam-engine practice the two usual cycles of operation used for comparative purposes are the Rankine and the Carnot cycles.

It is possible to compare the working of a steam engine with the theoretical working on the above ideal cycles by knowing the temperature limits, pressure, etc. of the actual case, and thus to express the relative efficiency of the actual and ideal performances. In internal-combustion-engine practice a similar mode of comparison is adopted, but the ideal cycles are not usually the same as for steam-engine work.

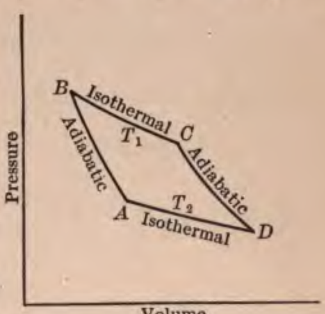


Fig. 4. The Carnot cycle

In the internal-combustion engine there are three possible cycles of operation of the working gas: (1) the constant-temperature, or Carnot, cycle; (2) the constant-volume, or Otto, cycle; (3) the constant-pressure, or Diesel, cycle.

1. *The Carnot, or constant-temperature, cycle.* This cycle of operations, performed upon a given mass of working substances, initially in a condition represented by the coördinates of point D (Fig. 4), consists as follows:

a. Isothermal compression at constant temperature T_2 along DA according to the relation $P_dV_d = P_aV_a = RT_2$.

b. Adiabatic compression along AB from volume V_a to volume V_b according to the relation $P_a V_a^n = P_b V_b^n$, the temperature increasing to T_1.

c. Isothermal expansion along BC at constant temperature T_1 according to the relation $P_b V_b = P_c V_c = RT_1$.

d. Adiabatic expansion along CD to the initial temperature T_2 according to the relation $P_c V_c^n = P_d V_d^n$.

Let V_a, V_b, represent the volumes of gaseous mixtures at A, B, etc.; P_a, P_b, etc., the corresponding pressures; and T_a, T_b, etc., the corresponding temperatures.

Then, for the adiabatic compression AB we have

$$\frac{T_1}{T_2} = \left(\frac{V_a}{V_b}\right)^{n-1} = \left(\frac{V_d}{V_c}\right)^{n-1},$$

so that
$$\frac{V_a}{V_b} = \frac{V_d}{V_c}.$$

During this cycle heat is absorbed only along the isothermal BC, and rejected during the isothermal compression line DA; that is, the heat absorbed along $BC = H_1 = RT_1 \log_e \frac{V_c}{V_b}$, and heat rejected along $DA = H_2 = RT_2 \log_e \frac{V_d}{V_a}$.

Hence the efficiency of the cycle, which is given by

$$\frac{\text{Heat absorbed} - \text{Heat rejected}}{\text{Heat absorbed}},$$

or
$$\frac{H_1 - H_2}{H_1} = \frac{RT_1 \log_e \frac{V_c}{V_b} - RT_2 \log_e \frac{V_d}{V_a}}{RT_1 \log_e \frac{V_c}{V_b}} = \frac{T_1 - T_2}{T_1}.$$

From these results it follows that the efficiency depends upon the initial and final temperatures of the gas; and, further, the greater the expansion the more efficient will the cycle become.

The practical employment of the Carnot cycle is, however, impossible. In an actual example worked out by Dugald Clerk

it was found that a maximum pressure reached during adiabatic compression was 500 pounds per square inch absolute; yet the mean effective pressure was only 6 pounds per square inch. These results indicate the impracticability of this type of cycle. The Carnot is a theoretical cycle, used only as a standard. To use this cycle would require higher pressures and temperatures than could be handled in practice.

2. *The Otto, or constant-volume, cycle.* This cycle is of the utmost importance on account of its wide adoption for internal-combustion engines.

The cycle of working changes is shown in Fig. 5, and consists of

a. Adiabatic compression of gas initially at A to B from volume V_a to V_b according to the relation $P_aV_a^n = P_bV_b^n$.

b. Addition of heat at constant volume V_b, and with rising temperature and pressure from B to C.

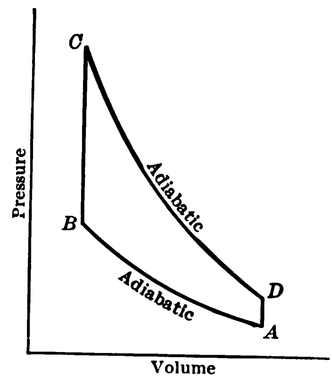


FIG. 5. The Otto, or constant-volume, cycle

c. Adiabatic expansion along CD to D, where $P_cV_c^n = P_dV_d^n$.

d. Rejection of heat at constant volume from D to A, with falling temperature and pressure.

We have here $$\frac{V_a}{V_b} = \frac{V_d}{V_c} = r.$$

Also, for the adiabatic, $$\frac{P_b}{P_a} = \left(\frac{V_a}{V_b}\right)^n = r^n,$$

so that $$P_b = P_a r^n.$$

For the adiabatic AB, $$\frac{T_b}{T_a} = \left(\frac{V_a}{V_b}\right)^{n-1} = r^{n-1};$$

that is, $$T_b = T_a r^{n-1}.$$

The only heat added during the cycle is during the change BC, and the only heat rejected is along DA.

Hence the heat absorbed along $BC = H_1 = C_v(T_c - T_b)$, and the heat rejected along $DA = H_2 = C_v(T_d - T_a)$, so that the efficiency

$$\frac{H_1 - H_2}{H_1} = \frac{T_c - T_b - T_d + T_a}{T_c - T_b} = 1 - \frac{T_d - T_a}{T_c - T_b}.$$

But $$\frac{T_b}{T_a} = r^{n-1} = \frac{T_c}{T_d}.$$

Then $$\frac{T_c}{T_b} = \frac{T_d}{T_a},$$

or $$\frac{T_c - T_b}{T_d - T_a} = \frac{T_b}{T_a}$$

and $$\frac{T_a}{T_b} = \left(\frac{T_d - T_a}{T_c - T_b}\right);$$

so that $$\text{Efficiency} = 1 - \frac{T_a}{T_b} = 1 - \left(\frac{1}{r}\right)^{n-1}.$$

This expression is similar to the one obtained for the Carnot cycle.

It will be seen that the efficiency depends upon the temperature at the commencement and end of the compression strokes; or, expressed in another way, the efficiency depends upon the compression ratio r.

The results of tests upon internal-combustion engines are now generally compared with the ideal performance of a quantity of air working upon the same Otto cycle and under the same conditions of compression, etc.

This is called the *air-standard efficiency*, and is given by

$$E_{air} = 1 - \left(\frac{1}{r}\right)^{.4} \text{ [since } (n-1) \text{ for air} = .4].$$

EXAMPLE. Suppose the condition represented by point A to be defined by $P_a = 1$ atmosphere (14.7 lb.), $V_a = 12.39$ cu. ft. (1 lb. of air), and $T_a = 492°$ F. absolute, and that $\frac{P_b}{P_a} = 7$, with 1000 B. T. U.'s added after compression.

Point B

$$\begin{cases} P_b = 7 \text{ atmospheres (assumed).} \\ V_b = V_a\left(\dfrac{P_a}{P_b}\right)^{.713} = 12.39\left(\dfrac{1}{7}\right)^{.713} = 3.09 \text{ cu. ft.} \\ T_b = T_a\left(\dfrac{P_b}{P_a}\right)^{.287} = 492\,(7)^{.287} = 859° \text{ F. absolute.} \end{cases}$$

Point C

$$\begin{cases} T_c = T_b + \dfrac{Q}{C_v} = 859 + \dfrac{1000}{.17} = 6741° \text{ F. absolute.} \\ P_c = P_b\left(\dfrac{T_c}{T_b}\right) = 7 \times \dfrac{6741}{859} = 54.9 \text{ atmospheres.} \\ V_c = V_b = 3.09 \text{ cu. ft.} \end{cases}$$

Point D

$$\begin{cases} V_d = V_a = 12.39 \text{ cu. ft.} \\ P_d = P_c\left(\dfrac{V_c}{V_d}\right)^{1.4} = P_c\left(\dfrac{P_a}{P_b}\right) = 54.9 \times \left(\dfrac{1}{7}\right) = 7.85 \text{ atmospheres.} \\ T_d = T_a\left(\dfrac{P_d}{P_a}\right) = 492 \times 7.85 = 3861° \text{ F. absolute.} \end{cases}$$

$$E_{air} = 1 - \left(\frac{1}{r}\right)^{.4} = 1 - \left(\frac{1}{7}\right)^{.4} = .54. \quad \text{(See Fig. 6.)}$$

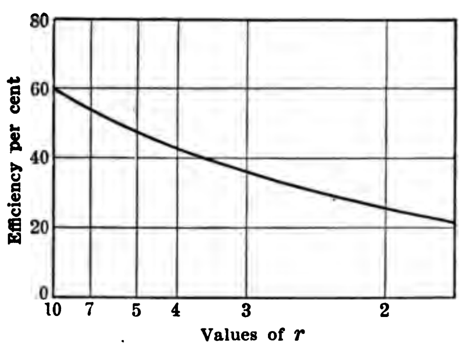


Fig. 6. Curve of air-standard efficiencies for different compressions ratios

In practical cases the expansion from the maximum pressure is not carried down to atmospheric, as the small gain in the mean effective pressure is more than counterbalanced by the size and weight of the engine.

3. *The constant-pressure, or Diesel, cycle.* This cycle is approximately followed in Diesel engines, and consists, theoretically, of two adiabatic and two constant-pressure operations. The sequence of operations is shown in Fig. 7.

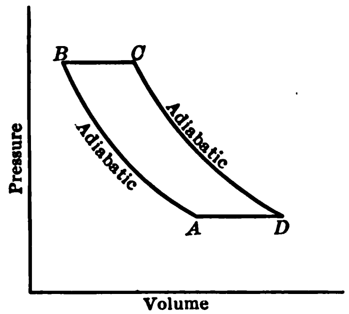


FIG. 7. The constant-pressure, or Diesel, cycle

a. Adiabatic compression along AB, where $P_a V_a^n = P_b V_b^n$.

b. Expansion at constant pressure with increasing temperature along BC.

c. Adiabatic expansion along CD, where $P_c V_c^n = P_d V_d^n$.

d. Compression at constant pressure, with decreasing temperature along DA to initial volume at A.

In this case, as in the Otto cycle, we have

Heat absorbed along $BC = H_1 = C_p (T_c - T_b)$.

Heat rejected along $DA = H_2 = C_p (T_d - T_a)$.

Whence, $$\text{Efficiency} = \frac{H_1 - H_2}{H_1} = \frac{T_c - T_b - T_d + T_a}{T_c - T_b}$$

$$= 1 - \frac{T_a}{T_b} = 1 - \left(\frac{1}{r}\right)^{n-1}.$$

It will be noticed that the efficiency is the same as for the Otto cycle, and that the efficiency depends upon the temperatures before and after compression; that is, upon the compression ratio.

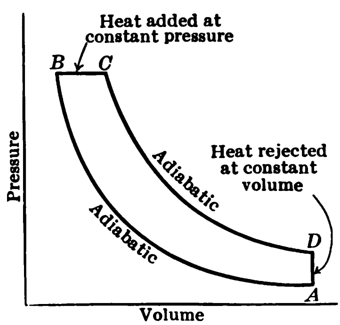


FIG. 8. The actual Diesel cycle

The *actual* Diesel cycle is shown in Fig. 8. Here, in place of heat rejected at constant pressure along DA, we have the heat rejected at constant volume with a falling pressure and temperature from D to A. In this case the heat rejected along $DA = H_2 = C_v (T_d - T_a)$.

Whence, $$\text{Efficiency} = \frac{H_1 - H_2}{H_1} = \frac{C_p(T_c - T_b) - C_v(T_d - T_a)}{C_p(T_c - T_b)}$$

$$= 1 - \frac{C_v(T_d - T_a)}{C_p(T_c - T_b)}.$$

But $$\frac{C_v}{C_p} = \frac{1}{n};$$

so $$\text{Efficiency} = 1 - \frac{1(T_d - T_a)}{n(T_c - T_b)}.$$

This type of cycle is closely followed in practice, except, of course, that the efficiency is not so high. Actually, engines working on this cycle show a much better efficiency, and therefore greater fuel economy, than when working on the Otto cycle.

Comparison of the cycles. If we consider constant-temperature, constant-volume, and constant-pressure cycles, it is evident from the similarity of the expressions for the efficiencies, namely,

$$E = 1 - \left(\frac{1}{r}\right)^{n-1},$$

that each of these cycles is capable of yielding efficiency depending entirely upon the degree of adiabatic compression.

The Carnot cycle, as already stated, is practically impossible, as its application would necessitate exceedingly great expansion and very high compression pressure, and then at best would only yield low effective pressures for useful work.

The remaining two cycles, then, are those of greatest interest to students of internal-combustion engines. In these cycles, it must be remembered that the compression pressure employable is limited by the safe maximum temperature. Remembering these limitations, the constant-pressure, or Diesel, cycle appears to be the appropriate one for internal-combustion engines.

The efficiences being equal, the question as to which type of cycle is the more suitable resolves itself into one of practical considerations. The Otto and Diesel cycles are of paramount importance in practice, and each is adapted to its own particular

field; for example, in one case the relatively greater fuel economy of the Diesel cycle may be of primary importance, whereas the weight and space may be of a secondary interest; and conversely for the other case.

It is necessary to emphasize the fact that the working gas, in the foregoing three possible cycles, has been pure dry air, obeying the ideal conditions, and that the ratio of the specific heats has been taken as being of constant value.

TABLE I. THERMAL PROPERTIES OF GASES

Name of Gas	Chemical Symbol	Density[1]	R	n	C_p	C_v
Air		0.08071	53.338	1.403	.2389	.1703
Nitrogen . . .	N_2	0.07829	54.737	1.4105	.2419	.1715
Hydrogen . . .	H_2	0.00562	768.267	1.408	.3410	.2422
Oxygen	O_2	0.08922	49.528	1.3977	.2240	.1603
Carbon Dioxide .	CO_2	0.12269	36.310	1.2997	.2025	.1558
Carbon Monoxide	CO	0.07807	53.726	1.3985	.2425	.1734
Marsh Gas . . .	CH_4	0.04470	110.719	1.316	.5929	.4505
Benzol	C_6H_6		66.789	1.4031	.2990	.2131
Ethylene . . .	C_2H_4	0.07951	49.450	1.1867	.4040	.3404

[1] Pounds per cubic foot at 32° F. and one atmosphere.

CHAPTER IV

GASOLINE AND OTHER INTERNAL-COMBUSTION-ENGINE FUELS

All internal-combustion-engine fuels contain the elements carbon and hydrogen. These elements, in chemical combination with oxygen, furnish the heat developed in the cylinder.

The principal products of nature convertible into use as fuel for internal-combustion engines are coal, oil, natural gas, and organic products for the manufacture of alcohol. Some of the artificial fuels available for the same purpose are illuminating gas, blast-furnace gas, producer gas, coke-oven gas, etc. In certain parts of the country, producer gas is used as a fuel in stationary internal-combustion engines, for it can be made very cheaply where low-grade fuels are available.

For developing the power of an internal-combustion engine any gaseous fuel is available, as well as any other fuel which can be vaporized or transformed into gas. By vaporized fuel we mean any fuel, such as gasoline, petroleum, oil, or alcohol, which may be used in the cylinder of a gas engine without the intermediate step of transforming it into a gas. There is no combustible substance which may not be transformed into a gas or have its gaseous products driven off by the action of heat. Any one of these fuels may be used efficiently in the cylinder of an internal-combustion engine. In all cases the power obtained from any fuel first converted into gas and then burned in the cylinder of an internal-combustion engine is greater than if the same amount of fuel were burned under an intermediate member such as a steam boiler and the steam used to run a steam engine.

The most important fuels for internal-combustion engines may be classified under two heads, *liquid fuels* and *gaseous fuels*. Of these the liquid fuels are the most generally used.

LIQUID FUELS

Under this head come crude oils and their distillates. Petroleum is a mineral oil composed of a series of hydrocarbons in various proportions, with some sulphur and other impurities. In the process of refining, the light oils are driven off by distillation at comparatively low temperatures. The first vapor given off is called petroleum ether and is but a small per cent of the whole. Next come gasoline, the naphthas, kerosene, and lubricating oils, in the order named. After distillation there is left about 18 per cent of paraffin wax and residuum.

By using a certain process called the "cracking" process, or destructive distillation, a considerable quantity of oils of a composition between kerosene and lubricating oil is converted into hydrocarbons of lower density and boiling point, and thus made suitable for fuel and illuminating purposes.

Gasoline. The average percentage composition of gasoline used in internal-combustion engines is as follows:

Carbon	83.5 to 85%
Hydrogen	15.5 to 15%
Nitrogen, oxygen, sulphur, etc.	1.0 to 0%

The higher heating value of gasoline lies between 19,000 and 21,000 B.T.U.'s per pound. The lower heating value ranges from 18,500 to 19,500 B.T.U.'s per pound. The specific gravity for this gasoline is from .67 to .73. For the combustion of 1 pound of gasoline the weight of air required is about 15 pounds; or the volume of air required at 62° F. is approximately 200 cubic feet. When gasoline is used as a fuel for internal-combustion engines, the liquid is vaporized and the vapor mixed with a suitable amount of air. One pound of gasoline vapor at 62° F. and atmospheric pressure has a volume of 4.2 cubic feet. With 15 per cent excess air, 1 cubic foot of vapor requires 54.2 cubic feet of air, and, taking 18,500 B.T.U.'s as the lower heating value per pound, the heating value per cubic foot of the normal charge is 69.3 B.T.U.'s.

Gasoline is a physical blend of hydrocarbons, all of which are sufficiently volatile to form an explosive mixture with air in proper proportion.

All gasolines are derived from crude petroleum, which is widely distributed in different countries of the world. The characteristics of crude oils obtained in different localities vary widely; hence gasolines made from them do not closely resemble each other, although to the layman they look very much alike. The difference in gasolines is particularly noticeable from a chemical viewpoint. For convenience all gasolines may be classified under four heads: (1) natural, (2) cracked, (3) by-product, (4) casinghead. The so-called natural gasolines are recovered from the first distillation of petroleum in crude-oil stills.

Gasolines are recovered as by-products from many other processes of refining, but as a whole these do not closely resemble the natural or straight-run gasolines. From still another source gasolines are recovered by compressing and condensing under pressure natural gases coming from crude-oil wells. Sometimes these gases are made to bubble through heavy oils which absorb the condensable portion. Subsequent distillation liberates the very light gasoline which the gases hold in solution. These volatile compounds are known as casinghead gasolines. They are much more volatile than other gasolines on the market, and are seldom used without blending. If employed in the same form as recovered, the evaporation losses in handling are so high as to render them uneconomical in use.

Very volatile gasolines, somewhat similar to casinghead gasolines, are recovered from gases coming from crude-oil and other stills. The same methods of compression, condensation, absorption, and distillation as with casinghead gasoline are employed. Cracked gasolines have come into general use during recent years and are now recognized as excellent motor fuels. In general terms the principles involved in the various cracking processes consist of decomposing or cracking petroleum products having a high boiling point, by means of heat and pressure, into a light volatile fraction, a heavy residual, and fre-

carbon. The distillate from the cracking still is the source of cracked gasoline. The calorific value of cracked gasoline compares very favorably with that of natural gasoline, the maximum difference between the two not exceeding 2 per cent. Well-known brands of gasoline now on the market are mostly mixtures from several different sources. These gasolines are mixed in such a way as to give the correct volatile properties required for motor fuels. They are generally as uniform in physical and chemical properties as production methods permit. For all practical purposes they may be considered as perfectly uniform in fuel value.

Many of the large refiners change the volatility of their gasolines with the summer and winter seasons. It is easily possible to utilize heavier gasolines in summer than in winter, and hence oil refiners are naturally ready to take full advantage of this fact, since the total output of motor fuel can thereby be greatly increased, to the mutual advantage of the consumer and the producer.

From the user's standpoint gasolines may be classified as natural, cracked, and casinghead, or variable mixtures of gasolines from these sources. Adulterations of different gasolines with kerosene are also sold as gasoline, but such mixtures are to be avoided, for many reasons hereafter given.

Many efforts have been made to arrive at some acceptable specification for the identification of motor fuel to be known as gasoline, but up to the present writing no such specifications have met with the universal approval of oil refiners. Much valuable work along this line has been done, however, and the study of various fuels for use in internal-combustion engines has at least brought to light the necessary requirements of such fuels from the standpoint of volatility, purity, and chemical and physical characteristics. It has been definitely decided by all concerned that gravity alone does not indicate the quality of gasolines.

All gasolines should be sufficiently volatile to render possible the easy starting of the motor at an average temperature. In

considering the subject of gasolines the most important point to bear in mind is that these hydrocarbon fuels are mixtures of different compounds which will boil at different temperatures. It is unnecessary that the entire body of the gasoline be sufficiently volatile to evaporate readily and completely at ordinary temperatures. In order to meet service conditions, however, there must be a sufficient quantity of volatile constituents to form an explosive mixture with air and thus start the motor. Once the engine is running, carburetion is much easier because of the heat conditions of operation. The functions performed by these light ends in a motor fuel is the same as that of kindling-wood in starting a fire. Kerosene contains no light ends, and heavy gasoline contains only a small amount, which is insufficient for starting; therefore neither kerosenes, heavy gasolines, nor a mixture of heavy gasolines and kerosenes can be used satisfactorily in a variable-speed, variable-load motor.

The operating temperature in variable-speed engines (other things being equal) is naturally lower than that of a constant-speed engine, such as an aircraft engine. After the pistons and cylinders of any engine have obtained their normal operating temperature, much heavier fuels may be successfully burned than those actually required for easy starting. In order to meet all conditions of operation, variable temperatures, and engine loads, a satisfactory gasoline must always contain a considerable amount of light ends to start the explosive fire of power delivery in an engine. Conservation of our natural resources demands that the less volatile motor fuels be used in greater quantities. The solution of this problem requires the application of properly designed preheating devices to all types of engines.

Unfortunately for the user, the full chemical and physical properties of gasoline can be dependably determined only in a laboratory by more or less experienced men. The burn test of gasoline is, however, very simple, and any engine operator can do this for himself by procuring a small porcelain crucible, pouring in about 30 cc. of the fuel to be tested, igniting it, and allowing it to burn freely to the end. The purity of the

This compression results in a temperature sufficient to ignite the oil spontaneously without the use of any ignition device. The fuel will be burned at constant pressure if the injection of the oil is properly regulated by the fuel valve.

Benzol. Benzol is a hydrocarbon product obtained from coke ovens and is used principally for denaturing and enriching alcohol, although it may be used as a fuel in its natural state. The specific gravity is .88. The higher heating value is about 18,000 B.T.U.'s per pound, and the lower heating value is about 17,300 B.T.U.'s. Benzol has the chemical formula of C_6H_6. For complete combustion of one pound of benzol 13.32 pounds of air are required. Benzol, when used in gasoline engines, will yield best results when the compression pressures are from 10 to 15 per cent higher than when gasoline is used.

The belligerent nations of Europe made wide use of a blend of 50 per cent of benzol and 50 per cent of alcohol as an engine fuel with excellent results, since this fuel can be used in the ordinary engine without change in compression ratio. A mixture of alcohol and benzol is now sold commercially in this country under various trade names. This mixture gives a high thermal efficiency and furthermore does not form carbon deposits in the cylinders, etc.

Alcohol. There are two kinds of alcohol that may be used for engine fuel: ethyl, or grain, alcohol (C_2H_6O); and methyl, or wood, alcohol (CH_4O). Both these alcohols have a specific gravity of about .80 at 62° F.

The laws of the United States require that alcohol used as a fuel must be denatured. Pure grain alcohol is denatured by adding 10 per cent by volume of methyl alcohol and one half of 1 per cent by volume of a heavy hydrocarbon called pyridine. The lower heat value of denatured alcohol is about 11,000 B.T.U.'s per pound.

A gasoline engine of ordinary design may burn alcohol with more or less success, but to secure the best results the carburetor must be adapted to the requirements of alcohol vaporization. When properly arranged, an engine will deliver slightly more

power with alcohol than with gasoline. Alcohol, being of known composition, unmixed with impurities other than water, has no inherent tendency to foul the interior of the cylinder. When employed in an internal-combustion engine, alcohol requires, for the best efficiencies, a compression pressure varying from 150 to 200 pounds, and then yields thermal efficiencies considerably higher than gasoline.

Alcohol may be used and stored with much less danger than gasoline, and in the matter of handling and the use of its exhaust products it is much more pleasant. Alcohol can be produced anywhere from the distillation of organic waste products.

A mixture composed of alcohol, kerosene, benzol, and ether is now manufactured commercially for use in the ordinary gasoline engines and has been found to work very satisfactorily and to give practically carbon-free conditions in the cylinder. This fuel is growing in popularity with engine operators.

Gaseous Fuels

The available gaseous fuels for power purposes are natural gas, illuminating gas, coke-oven gas, producer gas, and blast-furnace gas.

Natural gas is obtained from petroleum-bearing strata of rock at considerable depths below the earth's surface. This gas is most convenient for use in internal-combustion engines. It requires little cleaning; it usually contains no sulphuric or other acid-forming constituents and is very rich in heat-producing materials. Its heating value ranges from 900 to 1000 B.T.U.'s per cubic foot. The supply of natural gas, however, seems to be limited, and it is not, therefore, a fuel of as great commercial importance as might be expected.

Illuminating gas. This gas is used only for small engines or engines that run infrequently. This gas is clean and has a high calorific value, but the cost is prohibitive for power purposes. Its heating value is about 600 B. T. U.'s per cubic foot.

Coke-oven gas. Coke was formerly prepared in a type of oven called the "beehive coke oven," in which all the by-products

resulting from its manufacture were wasted. It is now made in a form of oven termed a "by-product coke oven," in which the by-products are saved and utilized. The gas which first comes from the oven is rich in hydrocarbons and is therefore used for illuminating purposes. The gas which comes from the oven after the coking process is nearly completed is available for power purposes. The gas must be cleaned before it can be used in an engine. It makes an excellent internal-combustion engine fuel and is used as such in localities where it is available. The heating value of one cubic foot of this gas is between 500 and 600 B.T.U.'s at 62° F.

Producer gas. Producer gas is a fuel made by converting solid fuel into gaseous fuel. Among the solid fuels that may be used for this purpose are coal, coke, lignite, and peat. In its simplest form the producer is a closed retort in which carbon is burned with a limited supply of oxygen. If, with the air, a proper proportion of steam is supplied, its decomposition in contact with the incandescent fuel will yield hydrogen. This hydrogen in the gas will tend to develop more power in the engine cylinder. The heating value of producer gas varies with the character of the fuel used in its manufacture. The average value is about 150 B.T.U.'s per cubic foot at 62° F.

Blast-furnace gas. Blast-furnace gas differs from producer gas only in that it contains very little hydrogen, and therefore is like the gas that would be made in a producer working without steam. Blast-furnace gas is low in heating value, varying from 95 to 105 B.T.U.'s per cubic foot at 62° F.

The gas as it comes from the blast furnace is charged with a large amount of dust, some of which is metallic oxide and readily falls out; the remainder is principally silica and lime, which is very fine and light. To remove this fine dust the gas should be passed through a scrubber, which cleans the gas thoroughly and has the additional advantage of cooling it. The use of this gas is of course limited to the iron-and-steel-making districts of the country.

CHAPTER V

COMBUSTION AND FLAME PROPAGATION

Combustion is defined as the chemical combination of an inflammable substance with oxygen. The result is heat, and the product of this combination is called an oxide.

In the burning of carbon, if the air or oxygen supply be limited, the total heat generated is limited. In this case we have imperfect combustion, the resulting product of combustion being mainly carbon monoxide. If the carbon burns to carbon dioxide, we have perfect combustion, the maximum possible amount of heat being generated or liberated for each pound of carbon burned.

The basis of the working of practically every internal-combustion engine is the chemical combination of the elements hydrogen (H) and carbon (C) with the oxygen (O) of the air.

From experiments made by various authorities the actual amount of heat evolved in the combustion of different elements with oxygen has been determined in each case. These heats of combustion are given in Tables II and III below.

TABLE II. CALORIFIC VALUES

Elements or Compounds	Symbol	B.T.U.'s per Pound	B.T.U.'s per Cubic Foot at 32° F. and Atmospheric Pressure
Hydrogen	H	62,100[1]	329[1]
Carbon	C	14,544	——
Carbon monoxide . . .	CO	4320	342
Sulphur	S	4000	——
Ethylene	C_2H_4	21,300	1700
Benzol	C_6H_6	17,976	3942
Marsh gas	CH_4	23,646	1066

[1] At 62° F. and atmospheric pressure.

TABLE III. CALORIFIC VALUES OF INTERNAL-COMBUSTION-ENGINE FUELS

Name of Fuel	Composition			Calorific Value in B.T.U.'s per Pound
	Carbon	Hydrogen	Oxygen	
	Per cent	*Per cent*	*Per cent*	
Alcohol	52.2	13.0	34.8	12,600
Methyl alcohol	37.5	12.5	50.0	9,500
Benzol	92.3	7.7	0.	17,976
Gasoline (density .68)	——	——	——	19,200
Gasoline (density .72)	85.	15.	0.	18,700
Gasoline (density .76)	——	——	——	18,250
Kerosene	84.5	15.5	0.	18,900
Acetylene	92.3	7.7	——	21,400
Fuel oil	87.	13.	0.	19,600

It will be noticed from Table II that the evolution of heat in the case of hydrogen combining with oxygen is roughly four times that of carbon and oxygen, so that fuels rich in hydrogen have high "calorific" values.

By the calorific value of a fuel is meant the total number of heat units evolved during the complete combustion of unit weight (1 lb.) of the fuel.

In the following considerations the atomic constitution of the molecule of each element is expressed by its chemical symbol. Thus, H_2, O_2, N_2, etc. are the chemical symbols for hydrogen, oxygen, and nitrogen respectively, and they further express the fact that one molecule of each of these elements contains two atoms. It is often necessary to be able to calculate the heat of combustion of a hydrocarbon fuel from its chemical composition; and for this purpose, besides knowing the chemical formula, it is also necessary to know the atomic weights of the elements.

Avogadro's law states that the weights of unit volumes of any of the gases whose atomic weights are known can be found. The atomic and molecular weights of various elements and compounds are given in the table following, as are also the number of pounds of air required for complete combustion of one pound of the substance in question.

TABLE IV. TABLE OF ATOMIC AND MOLECULAR WEIGHTS, ETC.

Element or Compound	Physical State	Symbol	Atomic Weight	Molecular Weight	Pounds of Air required per Pound of Substance
Carbon	Solid	C	12.	——	11.58
Hydrogen . . .	Gas	H_2	1.	2	34.64
Sulphur	Solid	S	32.1	——	4.35
Carbon monoxide	Gas	CO	——	28	2.48
Marsh gas . . .	Gas	CH_4	——	16	17.40
Acetylene . . .	Gas	C_2H_2	——	26	13.40
Benzol	Vapor	C_6H_6	——	78	13.40
Ethylene	Gas	C_2H_4	——	28	14.90
Alcohol	Liquid	C_2H_6O	——	46	9.10
Gasoline	Liquid	——	——	——	15.10
Fuel oil	Liquid	——	——	——	14.80
Oxygen	Gas	O_2	16.	32	——

Combustion of Carbon

The problem of finding the heating values of various elements and their compounds, and the air required per unit weight or volume, may best be solved by the use of simple chemical or combustion formulæ. Thus, when carbon is burned completely, we have

$$\underset{12}{C} + \underset{32}{O_2} = \underset{44}{CO_2}.$$

The numbers refer to the proportions by weight in which carbon and oxygen combine, and they show that 12 parts of carbon unite with 32 parts of oxygen by weight to form 44 parts of CO_2.

For each part of carbon completely burned to CO_2 there are required $\frac{32}{12} = 2.667$ pounds of oxygen. The heat evolved during the burning of 1 pound of carbon is 14,554 B.T.U.'s (see Table II). For incomplete combustion we have

$$\underset{24}{2\,C} + \underset{32}{O_2} = \underset{56}{2\,CO}.$$

Twenty-four parts of carbon are thus shown to unite with 32 parts of oxygen, forming 56 parts of carbon monoxide (CO). In other words, 1 pound of carbon requires $\frac{32}{24} = 1.33$ pounds

of oxygen to generate $\frac{56}{24} = 2.33$ pounds of CO. The heat generated in the partial combustion of 1 pound of carbon to CO is 4320 B.T.U.'s. The difference, $14{,}544 - 4320 = 10{,}224$, is still contained in the 2.33 pounds of CO. If this CO is not recovered and used, then the heat, of course, is lost, giving us the imperfect combustion referred to above.

The equation for combustion of CO is

$$\underset{56}{2\,CO} + \underset{32}{O_2} = \underset{88}{2\,CO_2},$$

which indicates that 1 pound of CO requires $\frac{32}{56} = .57$ pound of oxygen for its combustion, resulting in 1.57 pounds of CO_2.

It requires the same amount of oxygen to burn the carbon to carbon monoxide first, and then later to carbon dioxide, as is required to burn all the carbon to CO_2 in a single operation.

Combustion of Hydrogen

The combustion of hydrogen is a reaction represented by the formula

$$\underset{2\times 2}{2\,H_2} + \underset{32}{O_2} = \underset{36}{2\,H_2O},$$

indicating that 1 pound of hydrogen unites with 8 pounds of oxygen to form 9 pounds of water vapor.

When hydrogen is burned to water vapor at 62° F., the heat generated per pound of hydrogen is 62,100 B.T.U.'s.

Some of the internal-combustion-engine fuels, like natural gas and the artificial fuels produced from coal, contain heavy hydrocarbons. Of these the principal ones are marsh gas (CH_4) and ethylene (C_2H_4).

Both of these gases, when completely burned, form carbon dioxide and water vapor. Their chemical equations may be written as for carbon and hydrogen alone. Thus, for marsh gas we have

$$\underset{16}{CH_4} + \underset{64}{2\,O_2} = \underset{44}{CO} + \underset{36}{2\,H_2O}.$$

It will be seen that 1 pound of marsh gas will require $\frac{64}{16} = 4$ pounds of oxygen for complete combustion, resulting in

$\frac{44}{16} = 2.75$ pounds of carbon dioxide and $\frac{36}{16} = 2.25$ pounds of water. The heat generated by 1 pound of marsh gas is 23,646 B.T.U.'s; that generated by the combustion of 1 pound of ethylene is 21,300 B.T.U.'s.

In general it may be stated that the oxygen required for the combustion of any hydrocarbon is $2.667\,C + 8\,H$, where C and H are the proportions of carbon and hydrogen respectively entering into the composition.

Combustion in Air

The oxygen required for the combustion of all internal-combustion-engine fuels is obtained from the air. Since air contains but a small proportion of oxygen, it is necessary to determine the amount of air required for the combustion of 1 pound of the fuel in question.

Air is composed of 23 per cent of oxygen and 77 per cent of nitrogen *by weight*, and 21 per cent of oxygen and 79 per cent of nitrogen *by volume*. The other constituents of the air may be neglected in internal-combustion-engine calculations.

After the weight of oxygen required for combustion is found, it is easy to find the weight of air needed. Thus, for the complete combustion of 1 pound of carbon we have seen that 2.667 pounds of oxygen is required. Since the air contains 23 per cent of oxygen by weight, the air necessary to furnish 2.667 pounds of oxygen will be $\frac{2.667}{.23} = 11.58$ pounds.

In the case of hydrogen 8 pounds of oxygen is required, necessitating the use of $\frac{8}{.23} = 34.64$ pounds of air. (When fuels that contain oxygen are burned, the oxygen in the fuel may be subtracted from the theoretical amount required.)

One pound of air *by volume* at 32° F. occupies 12.39 cubic feet, and at 62° F. it occupies 13.14 cubic feet. After the weight of air has been found, the volume at 32° or 62° may be found by simply multiplying the weight by 12.39 or 13.14, according to the reference plane used. Thus, the 11.6 pounds

of air required to burn a pound of carbon to carbon dioxide would occupy a volume of 152.4 cubic feet at 62° F. and atmospheric pressure.

Higher and Lower Heating Value

Any gaseous fuel containing hydrogen will have what is called a higher and a lower heating value. The latter is always found by subtracting from the former the latent heat of the steam formed by the combustion of the hydrogen contained in the fuel. If we take the standard reference plane as 62° F. we must subtract from the higher heating value the latent heat of steam at 62°. This value of the latent heat may be obtained from any steam tables..

Flame Propagation

When an inflammable vapor or gas is mixed with air in certain proportions, the resulting mixture is found to be explosive, and the presence of a small flame or spark will cause the elements of the mixture to combine chemically, with more or less violence.

In internal-combustion engines the time of combustion must be exceedingly small if efficiency is to be secured. The explosion should always be as near complete as possible before the expansion stroke begins, and should not start too soon toward the end of the compression stroke or the work of compression will be too great. To get an idea of the time available for the time of combustion, assume an internal-combustion engine running at 1200 revolutions per minute, or 20 revolutions per second, completing one revolution in one twentieth of a second. Then, if we allow 15 degrees of crank rotation near the dead center for the ignition and combustion, we have $\frac{15}{360} = \frac{1}{24}$ of a revolution, or $\frac{1}{24} \times \frac{1}{20} = \frac{1}{480}$ of a second allowable for the whole process. From this it can be seen that the flame speed must be very high in order that the mixture may be completely burned in such a short space of time.

In the transmission of the explosion two distinctly different processes may be noted: (1) in the process of *slow combustion* the layers of gas adjacent to the ignited layer are brought to the temperature of ignition by conduction; (2) an explosion may be transmitted by a *combustion wave* which is transmitted simultaneously with the ignition at a speed of several thousand feet per second. The latter process is the one used in nearly all engines using gasoline or similar fuels.

The speed with which flame spreads through a mixture of fuel gas and air depends upon the following factors: (1) the composition of the mixture; (2) the pressure, or amount of compression; (3) the temperature of the mixture; (4) the location of the point of initial ignition; (5) the fact that the flame propagation is much greater when the mixture is ignited at constant volume than when ignited at constant pressure.

1. The rate of flame propagation is much lower with diluted mixtures than with rich mixtures, and in many cases is so low as to have a bad effect on the efficiency of the engine.

2. Increasing the pressure of the explosive mixture, that is, increasing the compression pressure of the charge in an internal-combustion engine, has the effect of increasing the flame propagation throughout the mixture. This fact is taken advantage of in racing and aircraft engines.

3. The rate of flame propagation is increased as the temperature of the mixture is raised.

4. To insure a high rate of flame propagation the location of the point of initial ignition should be as near as possible to the center of the compressed mass of the mixture.

5. The flame velocity is much greater when the mixture is exploded under conditions of constant volume (Otto cycle) than when under constant pressure (Diesel cycle). This fact is established by experiments made upon mixtures of hydrogen and oxygen in open and closed tubes.

In the case of the Otto cycle engine, ignition at constant volume can occur only at the dead-center position, when the piston is momentarily stationary, so that for maximum flame

velocity it is important to ignite as near the dead center as possible, at the same time bearing in mind the necessary time interval elapsing between the moment of ignition and the attainment of possible pressures.

The measured flame speeds in the experiment above mentioned were found to be 66 feet per second for explosion at constant pressure, and 3280 feet per second for explosion at constant volume.

For convenience of reference the following table is given here and contains some of the usual compression pressures and temperatures for internal-combustion engines.

TABLE V. THE USUAL COMPRESSION PRESSURES AND COMPRESSION TEMPERATURES FOR INTERNAL-COMBUSTION ENGINES

Type of Engine	Fuel	Range of Compression (Pounds per Square Inch Gauge)	Average Compression (Pounds per Square Inch Gauge)	Temperature of Compression (Degrees F.)
Automobile	Gasoline	45–95	65	390°
Stationary	Gasoline	60–105	70	405°
Hot bulb, 250–500 r.p.m. .	Kerosene	30–75	60	375°
Vaporized entering cylinder	Alcohol	120–210	150	590°
Injected after compression .	Fuel oil	255	255	775°
Diesel cycle	Fuel oil	510	510	1000°
Medium and large engines .	Natural gas	75–160	120	530°
Large engines	Coke-oven gas	105–135	120	530°
Mostly small engines . . .	Marsh gas	75–105	90	460°
Both large and small engines	Producer gas	100–160	130	550°
Largest engines built . . .	Blast-furnace gas	120–190	155	600°

CHAPTER VI

THE OTTO AND DIESEL CYCLES IN PRACTICE

Under the general heading Internal-Combustion Engines are included all engines which develop their power by the combustion within their cylinders of some form of inflammable gas, or liquid hydrocarbons and their derivatives, mixed with air. In this branch of power generation two well-defined principles are involved: (1) the Otto, or constant-volume, cycle, and (2) the Diesel, or constant-pressure, cycle.

Engines operating on the Otto cycle mix the fuel and air before or during compression, and always depend upon an outside source of heat (electric spark, or hot tube) for igniting the explosive charge at the proper instant while under compression. The fuel is introduced into the cylinder as a gas or in a highly atomized form mixed with air, and the heat generated by compression completes the gasification. Different fuels mixed with air have different ignition temperatures, and consequently, to avoid premature ignition, different compression pressures must be prescribed for each fuel.

Engines operating on the Diesel cycle inject the liquid fuel, finely atomized by air under high pressure, into the combustion chambers which contain only *pure air* previously compressed to such a degree as to obtain a temperature far above that of the ignition point of the fuel. At the average compression of about 500 pounds per square inch the temperature of the air in the cylinders of the Diesel engine is much greater than is actually necessary to ignite the charge of fuel and air. Combustion is therefore rapid and complete, and continuous as long as fuel is supplied. This *combustion* is in contradistinction to the *explosion* which follows ignition in the Otto-cycle engine.

The Otto Cycle Engine

The Otto cycle engines are designed to perform 2-stroke or 4-stroke cycles per power stroke.

In either type there are four operations to be accomplished during each cycle: (1) drawing in a fresh charge of gas and air into the cylinder; (2) compressing and igniting the explosive mixture; (3) expansion of the ignited charge and absorption of its energy; (4) expulsion of the burned gases.

The *2-cycle*, or *2-stroke-cycle, type* of internal-combustion engine is used to a very limited extent as the motive power of automobiles, but to a much greater extent for the propulsion of motor boats. The 2-cycle engine has no valves, the gas entering and exhausting through ports in the cylinder walls, covered and uncovered at proper intervals by the travel of the piston up and down.

There are two different types of 2-cycle engines. (1) the *2-port* engine, and (2) the *3-port* engine.

The Two-Port Engine

The general outline of the 2-port, 2-cycle engine is shown in Fig. 9. *C* represents the cylinder; the piston *P* moves freely up and down in the cylinder; the connecting rod *R* connects the piston with the crankshaft *S*. As the piston moves up and down it imparts a rotary motion to the crankshaft by means of the connecting rod. The crankcase *B* is made gas-tight. An opening into the crankcase is provided with a check valve *V*, which allows gas to enter the crankcase but not to pass out. A transfer passage *T* leads from the base and opens into the cylinder at the inlet port *I*, which is above the piston when the latter is at the lowest point of its stroke, as in Fig. 11. Another port, called the exhaust port, opens from the cylinder to the outside at *E*.

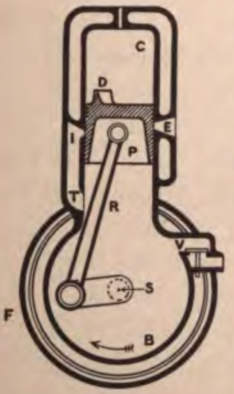


Fig. 9. Diagrammatic view of 2-cycle, 2-port engine

The exhaust port is somewhat higher up than the inlet port. Both inlet and exhaust ports are covered by the piston except when it is near the bottom of its stroke. The flywheel F is provided to give a steady rotation. A projection, or deflector, D, on the piston directs the inlet gas upward toward the head of the cylinder, thus avoiding a loss of the fresh charge with the exhaust gases.

FIG. 10. Mixture entering the crankcase

The dimensions of the crankcase are reduced to the smallest possible volume, so as to afford compression of the explosive mixture within the crankcase when the piston descends.

The fundamental difference between the operations of the 4-cycle and 2-cycle internal-combustion engines should be borne in mind at this point. In the 4-cycle single-acting engine all operations take place separately within the cylinder above the piston, whereas in the 2-cycle engine the operations take place on both sides of the piston, that is, within the cylinder and within the crankcase, two operations occurring at each stroke, instead of one operation, as in the 4-cycle engine. In the 2-cycle engine an explosion takes place and power is delivered once every two piston strokes, or once every revolution.

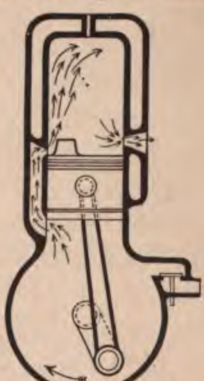


FIG. 11. Mixture entering cylinder

The operations in a 2-port, 2-cycle engine are as follows: Suppose the piston to be at the bottom of its stroke, and to ascend, as in Fig. 10. This action will create a partial vacuum, or "suction," in the crankcase and will draw in a charge of explosive mixture through the carburetor and check valve.

When the piston descends, as in Fig. 12, the explosive mixture is compressed within the crankcase, and at the lowest position of the piston in the cylinder the inlet port is uncovered

and the compressed charge from the crankcase escapes into the cylinder, filling the same, as in Fig. 11. However, before any of the new charge can escape through the exhaust port *E*, which is also open, the piston has begun its next upward stroke and covered both ports, so that the cylinder is filled with nearly fresh gas. As the upward stroke continues, the charge in the cylinder is compressed into the space above the piston, while at the same time a new charge is being drawn into the crankcase. When the piston has reached the top of the stroke, the compressed charge is ignited and the exploded gases drive the piston downwards, permitting expansion, delivery of power, and the compression of a new charge within the crankcase. As the piston nears the bottom of its stroke, it uncovers the exhaust port *E*, allowing the pressure in the cylinder to drop and a part of the burned gases to escape. An instant later in the stroke the inlet port *I* is uncovered and a fresh charge is admitted from the crankcase. This rapid inrush of the new charge aids materially in driving out the burned gas through the exhaust port. The new charge is then compressed on the up-stroke and a new supply drawn into the crankcase. From this point the cycle of operations is continuously repeated.

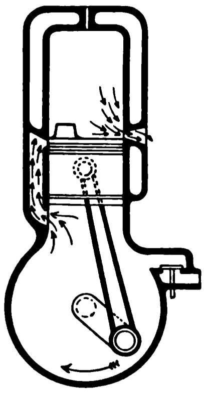


FIG. 12. Exhaust gases escaping from cylinder and fresh mixture about to enter

Following through the sequence of operations, it will be seen that the cycle is completed during every revolution, or for every two strokes. The momentum of the flywheel is depended upon to carry the piston up during the compression stroke.

The exhaust port is usually opposite and somewhat higher up than the inlet port, in order that the pressure may be reduced and the burned gases partially escape before the fresh charge is admitted. If this were not done, the temperature in the cylinder would be so great that the incoming charge would be fired prematurely. The relative position and size of the inlet

and exhaust ports is the key to the success of the 2-cycle engine. The piston, in this type of engine, acts as its own valve, so that the engine, from its very principle, is valveless.

The Three-Port Engine

In the 3-port engine, shown in Fig. 13, the third port *K*, leading from the carburetor to the crankcase, is closed by the piston before the crankcase compression stroke, and no check valve between crankcase and carburetor is necessary, as in the 2-port engine.

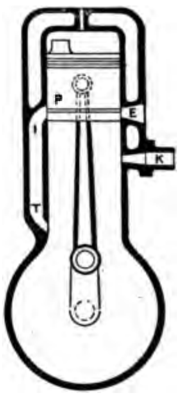


Fig. 13. Diagrammatic view of 2-cycle, 3-port engine

The operation of the 3-port engine differs somewhat from that of the 2-port. As the piston ascends on the inlet stroke an increasing vacuum is created within the crankcase until the lower part of the piston uncovers the third port and thus allows the inrushing mixture from the carburetor to fill the crankcase. As the piston descends the third port is again covered and the explosive mixture is compressed within the crankcase. At the lowest position of the piston in the cylinder the inlet port *I* is uncovered and the compressed charge escapes into the cylinder. In all other respects the cycle of operation within the cylinder and the crankcase of the 3-port engine is exactly the same as in the 2-port engine.

The table below, covering two revolutions, indicates the frequency of power delivery and other operations of a single-cylinder 2-cycle engine.

Operations	One Revolution		One Revolution	
	Down-stroke	Up-stroke	Down-stroke	Up-stroke
In Cylinder	*Explosion* Exhaust Inlet	Compression	*Explosion* Exhaust Inlet	Compression
In Crankcase	Compression Discharge	Inlet	Compression Discharge	Inlet

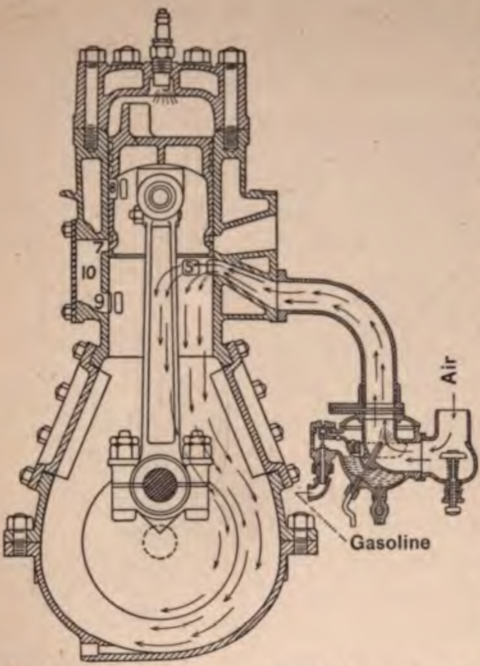


FIG. 14. End of compression stroke on 2-cycle, 3-port engine. The third port (5), leading from carburetor to crankcase, is open

The navy-type gasoline engines are 2-cycle, 3-port, as shown in section in Figs. 14 and 15. The operation of this engine is the same as the 3-port engine described above, except that the transfer of the mixture from the crankcase into the cylinder is made through ports (8) in the piston, which register with ports (9) in the cylinder wall and admit the mixture into the transfer passage (10), from which it passes into the cylinder through the inlet ports (7), as in the above types.

THE FOUR-CYCLE, OR FOUR-STROKE-CYCLE, ENGINE

This type of internal-combustion engine is generally employed for the propulsion of automobiles, pleasure boats, etc. and is almost universally used in aircraft engines. The intake and exhaust valves are operated by mechanical means.

Referring to the four views in Fig. 16, which illustrate the four strokes forming the complete cycle, *I* is the inlet valve opening from the admission chamber into the cylinder, and *E* is the exhaust valve opening from the cylinder into the exhaust chamber. These valves are controlled by an operating mechanism from the engine shaft. The other parts of the engine are substantially the same as the 2-cycle engine, except that the crankcase need not be gas-tight.

Intake stroke. In Fig. 16 the suction caused by the piston starting downward, as the engine is cranked, draws the explosive mixture into the combustion chamber of the cylinder. It enters through the inlet valve *I*, which is the only opening. The exhaust valve is closed, the inlet being so adjusted that the cam opens it mechanically as the suction action of the piston commences.

Compression stroke. Here we have both valves closed as the piston starts on its upward stroke, and the charge in the cylinder is compressed into the small space of the combustion chamber as it reaches the top of the stroke.

Power stroke. Here again both valves are still closed, and as the piston reaches the top of the stroke the spark is timed to jump the spark-gap points and ignite the compressed explosive mixture. The piston is driven down by the expansion of the gas, making the power stroke.

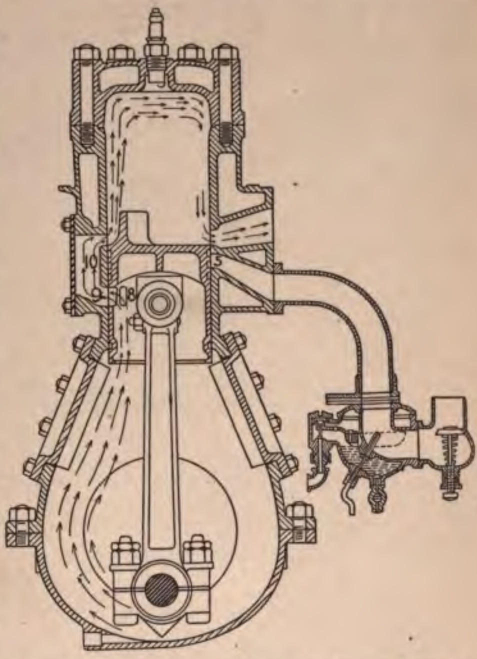


FIG. 15. End of explosion stroke on 2-cycle, 3-port engine, showing the exhaust and inlet ports open

Exhaust stroke. In this view as the piston returns from the power stroke the exhaust valve is opened, the pressure remaining from the explosion forcing out the burned gas. The upward movement of the piston pushes out the burned gas that does not escape by its own pressure.

The exhaust valve closes as the piston reaches the top, and the inlet valve opens to admit a fresh charge of gas into the

cylinder. The operation is then repeated as long as the engine runs. The cycle is completed in two revolutions, or four strokes, and is therefore called the 4-cycle, or 4-stroke, engine. There are three idle strokes and one working, or power, stroke during

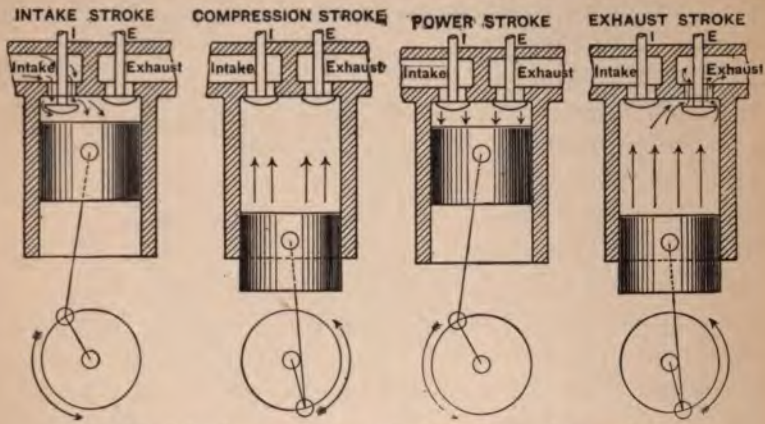


FIG. 16. The four strokes required for a complete cycle in a 4-cycle engine

each cycle, thus giving a power stroke for each alternate revolution. The flywheel must be heavy enough to carry the piston through the three idle strokes.

COMPARISON OF THE ADVANTAGES OF EACH TYPE

The 2-cycle engine has the advantage of extreme simplicity, owing to the absence of valves or other moving parts which would be likely to need adjustment and care. As the piston receives an impulse during each revolution, more power may be obtained from the same size cylinder than in the 4-cycle type. It might seem that, since the 2-cycle engine receives twice as many impulses as the 4-cycle, twice the power should be obtained; but this is not the case, because owing to the superior regulation of the 4-cycle type, the difference is much less. The more frequent occurrence of the impulse does, however, allow the use of a lighter flywheel, and produces a smoother running engine with less vibration.

The valveless feature of the 2-cycle type, while giving simplicity, at the same time gives rise to some irregularities in the action of the engine. The action of the gas in the cylinder is somewhat uncertain; it is hardly to be expected that the inflow of gas will continue exactly long enough to fill the cylinder, and no more; it is entirely possible that either some of the exhaust gases may not have time to escape or that some of the fresh charge may pass over and out through the exhaust. Again, it is hardly possible for the incoming gas to scour the entire upper parts of the cylinder. Some waste gas is sure to be caught, thus diluting the new charge. The driving out of the burned gas by the fresh mixture while some combustion may still be going on frequently results in the premature ignition of the new charge, the flame following down the transfer passage and igniting the reserve charge in the crankcase. This produces a back explosion and a crankcase explosion, causing irregular action, sometimes even stopping the engine and doing considerable damage.

There are some disadvantages which may be termed structural. While the working parts are simple, they are entirely inclosed and are not easily examined or adjusted. As the crankcase must be gas-tight, any leakage around the crankshaft bearings from natural wear causes a loss of crankcase pressure, with consequent loss of power. Any leak around the piston will allow the partially burned gases to pass down and deteriorate the quality of the fresh gas in the crankcase. The lubrication of the parts in the closed crankcase, which are exposed to the direct action of the fuel gas, is sometimes difficult.

The 4-cycle type, although more complicated, is surer and more certain in its action, as the behavior of the gas is mechanically controlled. The idle stroke allows the cylinder a short time to cool between explosions. On account of the mechanical regulation there is less chance for waste of fuel, and the economy is therefore greater than that of the 2-cycle engine. As the flow of gas into the cylinder is steady throughout the stroke, instead of in sudden puffs, the 4-cycle engine may be

run economically at a higher rate of speed. No inclosed crank-case is necessary, and the working parts can therefore be more easily lubricated and adjusted.

The three idle strokes of the 4-cycle engine require a comparatively heavy flywheel, and as the impulse occurs only on alternate revolutions, the 4-cycle engine must, for the same power, be larger and heavier than the 2-cycle. Each impulse, or explosion, is much stronger than in the 2-cycle engine, hence the tendency to vibration is greater.

Thermal efficiencies of the 4-cycle and 2-cycle engines. The greatest possible thermal efficiency of a gasoline engine working under ideal conditions (that is, with no thermal losses to the water jacket, etc.) is 25 per cent less than the air-standard efficiency, which itself depends upon the compression ratio employed (see Chapter III).

In the case of gasoline engines of the touring-car type the compression ratio lies between 3 and 5, and corresponding to this upper limit the highest efficiency that could be obtained would be about 38 per cent.

When one considers that the thermal efficiency of the modern 4-cycle engines is in the neighborhood of from 28 to 30 per cent, as the results of numerous scientific tests have shown, it will be realized how very efficient this type of internal-combustion engine is and what a small range of possible improvement is left.

Considering the elementary type of 2-cycle engine in which the piston uncovers the exhaust and inlet ports respectively, measurements of the thermal efficiency of this type of engine show that the maximum efficiency obtainable under the best conditions of mixture strength, speed, etc. is about 23 per cent for compression ratios between 3 and 5.

The relatively lower efficiency of the 2-cycle engine is no doubt due to the charge wastage which is associated with the design of the engine. In the better designs of the engine, where the overlapping of the ports cannot occur, or is at least reduced, higher efficiencies may be expected. When due allowance is

made for the amount of fuel which passes out with the exhaust gases unconsumed, so far as the engine is concerned, the net thermal efficiency attains a value of about 26 per cent.

It is probable that the relatively higher cylinder temperatures of the 2-cycle engine will tend toward higher thermal efficiencies, and that, generally speaking, there is not much to choose between the 2-cycle and 4-cycle engines in the matter of thermal efficiency in well-designed types.

Heat balance. The heat balance of the average Otto-cycle engines operating under full load is approximately as follows:

	PER CENT
Heat equivalent of work done	32
Heat carried away by cooling water	27
Heat rejected in exhaust gases	36
Heat lost by radiation, etc.	5
	100

GENERAL CONCLUSION

It may be stated as a general conclusion that for small, light engines which receive little attention and where economy is not of great importance, the 2-cycle type is to be preferred. For single-cylinder engines the 2-cycle type is decidedly to be preferred because the vibration is less than in the single-cylinder engine of the 4-cycle type. For engines of larger size, where increased reliability is demanded and fuel economy becomes of importance, the 4-cylinder type is preferable.

THE DIESEL-CYCLE ENGINE

The Diesel-cycle engines are also designed to perform 2-stroke or 4-stroke cycles for every power stroke. The marine engines are usually single-acting and are built in the vertical type only.

FOUR-CYCLE DIESEL

A representative engine of the 4-cycle type is shown in Fig. 17. The piston *A* makes four strokes — two up and two down — for every power stroke that takes place.

Intake stroke. During the first downward stroke of the piston *A*, the intake valve *B* on the working side of the engine opens,

and through the intake valve *C* pure air only is drawn into the cylinder *D* by the downward, or suction, stroke of the piston.

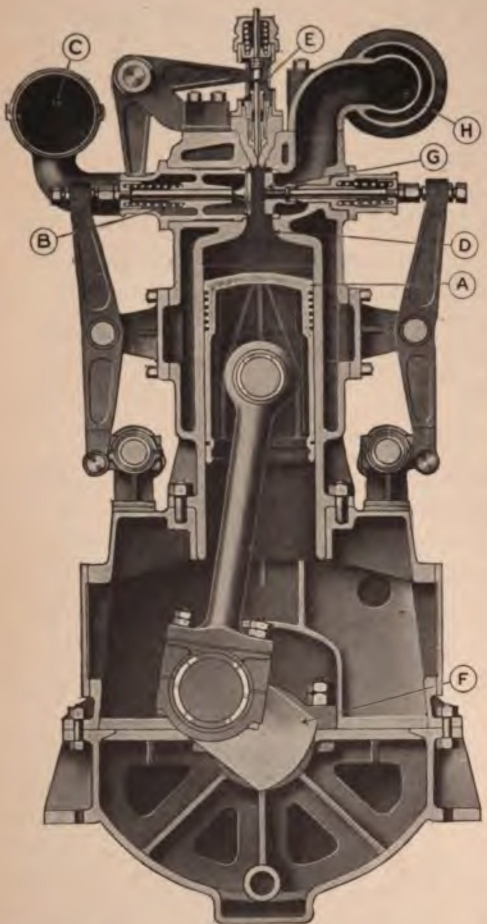


FIG. 17. Representative 4-cycle Diesel engine

A, piston; *B*, intake valve; *C*, intake manifold; *D*, cylinder; *E*, fuel valve; *F*, crankshaft; *G*, exhaust valve; *H*, exhaust manifold

Compression stroke. When the downward stroke is complete, the intake valve *B* closes, and the upward stroke of the piston compresses the air, thereby raising its temperature to the point where it will ignite and completely burn fuel oil or crude oil. This compression continues until the piston reaches the limit of its upward travel.

Combustion stroke. At this moment the fuel valve *E* opens, a charge of fuel oil is sprayed into the hot air in the cylinder, instantly the oil ignites, and the expansion of the burning gas forces the piston downward, turning the crankshaft *F*. This is the power stroke.

Exhaust stroke. The momentum of the flywheel causes the crankshaft to continue to turn and again forces the piston upward. During this upward stroke the exhaust valve *G* opens, and

the upward movement of the piston forces the burned gas out of the combustion chamber through the exhaust manifold *H*.

This 4-stroke cycle is repeated in each cylinder of the engine once in every two revolutions of the crankshaft. The Diesel engine makes full use of the heat of compression, so no other means of ignition is necessary. The fuel is fed into the fuel chamber in the proper amount by a small pump. At the time of maximum compression the fuel valve is opened by means of cams and rockers, and the fuel is blown into the cylinder against the compression by great air pressure.

The various parts of the Diesel engine are, in comparison with the cylinder bore, much heavier and stronger than in the Otto cycle engine. This is due to the greater pressure employed and to the consequent greater stresses.

It is not essential that the particular arrangement of valves shown should be used. This has been chosen as representing a successful type and also showing well the relation of the various parts. It is quite customary to arrange the valves side by side in the head, with the fuel valve at the top; but in every case it is usual to place the valves in the head, as this gives the strongest construction. The compression space can thus be easily kept as small as is necessary to secure high compression.

A continuous supply of high-pressure air must be available for fuel injection in the Diesel engine. Also, a supply of moderate-pressure air is necessary for starting. The air for both these purposes may be supplied by an air compressor driven from the crankshaft at one end of the engine.

In the 2-cycle type the action as regards compression and fuel injection is the same as above described; near the lower end of the stroke, however, the piston uncovers ports through which the burned gas escapes, as in the 2-cycle Otto engine. Valves in the head then admit air which scavenges the cylinder of the remaining burned gas and furnishes pure air for the next compression stroke.

In the Diesel engine the admission and burning of the fuel extends over an appreciable part (about one tenth) of the

power stroke. The maximum pressure is therefore not raised greatly above the compression pressure, and the impulse is comparatively steady over the first part of the stroke, after which the pressure falls by expansion to the exhaust pressure.

Advantages and Disadvantages of the Diesel Engine

Some of the advantages of this engine for marine purposes are as follows:

1. Less space necessary than that required for the steam engine and boilers.

2. Less attention necessary than with the steam engine, thus reducing the working force required in a steamship.

3. Greater facility for storing and replenishing oil fuel as compared with coal.

4. Increased steaming radius possible on account of the greater economy of the oil engine as compared with the steam engine.

5. Absence of large funnels and the elimination of smoke and cinders.

6. Ability to get under way quickly. The engine can be started at a few moments' notice.

7. Elimination of stand-by losses. As soon as the engine stops, the fuel consumption ceases.

Some of the disadvantages of the Diesel engines for ship propulsion are as follows:

1. Lack of reliability. The steam engine, even with improper handling and with breakdown, can be temporarily repaired and brought into port, whereas the Diesel engine under the same conditions and with the same handling might be helpless.

2. A higher grade of skilled attention required than for the steam-engined ship.

3. More difficult to keep adjusted than the steam engine.

4. More difficult to locate and remedy troubles than in a steam engine.

5. The necessity for maintaining a plentiful supply of compressed air for starting and maneuvering.

Many of these disadvantages will undoubtedly disappear as the Diesel engine becomes more generally used for marine purposes than it is at present.

Thermal Efficiency and Economy of the Diesel Engine

The thermal efficiency and economy of the modern Diesel 4-cycle engine operating at full capacity is greater than that of the Otto engine. The thermal efficiency is from 32 to 35 per cent for the 4-cycle engine; that for the 2-cycle engine under similar conditions is approximately 3 per cent less.

Heat balance. The heat balance of the average Diesel engine showing the distribution of the heat per pound of fuel received into its cylinders is approximately as follows:

	Per Cent
Heat equivalent of work done, including friction and air compressor	43
Heat carried away by cooling water	33
Heat rejected in exhaust gases	23
Heat lost by radiation, etc.	1
	100

CHAPTER VII

CARBURETION AND CARBURETORS

Carburetion is the art of mechanically mixing or blending a liquid fuel with a certain amount of air. Whether or not this art is carried to perfection is an indication whether the carburetion is good or bad.

Fuel may be mixed with air in several ways. The first and oldest form of carburetion is that accomplished by passing air through a mass of liquid fuel. On the other hand, a volume of air may be treated by spraying into it a certain quantity of fuel in a more or less finely divided state. This latter principle is the one embodied in all modern carburetors.

There is probably no part of a modern internal-combustion engine which has undergone more useful development in recent years than the carburetor. The improvements which have taken place have made it possible to obtain that great range of speeds in engine rotation with which we are all now familiar. Furthermore, these results have been accompanied by other advantages, such as the reduction of fuel consumption, more nearly perfect combustion, the prevention of overheating, and ease of starting.

The perfect speed control of modern multicylinder motors is principally dependent on a self-adjusting form of carburetor which will automatically and positively carburet the air to form a mixture of an exactly predetermined degree under all conditions of temperature, load, and speed.

In the case of an ordinary mixture of hydrocarbon vapor and air there are two limits, an upper and a lower, between which such a mixture will be combustible under normal conditions. The completeness of combustion depends upon the correct proportioning of air to fuel. When the fuel is in excess,

carbon monoxide is formed as a product of combustion; when air is in excess, the exhaust gases will show oxygen to be present.

It is the function of the carburetor to deliver to the engine, under all conditions of load, speed, and throttle opening, a mixture of such proportions of gasoline and air as will result in the most complete combustion and maximum power. This proportion has been found to consist of approximately one part of gasoline to fifteen parts of air, by weight.[1]

A mixture composed of more than one part of gasoline to fifteen parts of air is termed *rich*, while one containing less than one part of gasoline to fifteen of air is termed a *poor*, or *lean*, mixture. A rich mixture will give a slight increase of power in many carburetors, but at the expense of thermal efficiency.

It is a well-known fact that, in order to change the state of a body from a liquid to a gas, heat must be applied, and the amount of this heat must be equal to the latent heat, or heat of evaporation, of the fuel. To attain this evaporation with gasoline the temperature of the air entering the carburetor should be about 80° F. for medium-speed engines. If the engine speed is higher, so that the fuel does not have sufficient time to absorb the necessary heat in the carburetor or induction pipe, the temperature of the air should be higher.

We now come to the explanation of a fact not generally understood, — that a fixed carburetor, in which the relations between the air flow and the fuel flow are predetermined, does not always work well until it is warmed up, and that it is sometimes necessary to flood the carburetor, or prime the cylinders, before the engine will start. This is due to the absence of a heat supply sufficient to effect carburetion. It is absolutely essential for their working that the so-called automatic carburetors be heat-jacketed in some way. These carburetors are difficult to start and will not work until properly warmed up. If in a properly designed automatic carburetor the fuel is correctly proportioned for running under normal conditions, then when the conditions are abnormal, as in starting, the air suppl

[1] By volume, this would be about 1 volume of gasoline to 10,000 volumes of ai

must be decreased or the fuel supply temporarily increased. It is possible, of course, to add heat to the liquid fuel before it is mixed with air; but as the relative weight of liquid to air is small, it would be impracticable to add sufficient heat to the liquid in order to supply the necessary thermal units required for the latent heat of evaporation. The specific heat of the liquid is about three times that of air, and as there is about fifteen times as much air as fuel by weight, it is plainly seen that it would be necessary to raise the temperature of the liquid through five times the range that is necessary when dealing with air. This is quite impossible, as some of the lighter fractions of the fuel begin to distill off at fairly low temperatures. Some carburetors do heat the liquid, but not to any great extent.

A hot-water jacket on a carburetor, in addition to heating the incoming air, does of course heat the fuel; but it has been found in modern practice that an extension of the heating-jacket is necessary, and the jacket is therefore carried a considerable distance along the induction pipe. Formerly carburetors were not water-jacketed, nor was any special provision made for supplying warm air to the carburetor. To-day both these measures are resorted to, in order to give good results.

In using kerosene or alcohol for fuel the question of preheating becomes still more important. With kerosene it is necessary to supply heat, because it is less volatile at ordinary temperatures and pressures than gasoline. With alcohol the same difficulty presents itself, and in addition the water which is always present in commercial alcohol gives trouble.

The gasoline carburetor is not well adapted for using kerosene as fuel even if provision is made for jacketing with hot water and supplying hot air. Almost any gasoline engine which has been operated long enough to have reached a constant temperature can be made to continue in operation on a mixture of kerosene and air formed in the same gasoline carburetor. The operation will, however, be uncertain, and it will be only a matter of a short time before the interior of the

combustion chamber is covered with a deposit of carbon and the piston rings are gummed tight in their grooves.

It has been found that a certain amount of finely divided water spray mixed with the kerosene-air mixture materially improves the behavior of the engine. The presence of water decreases the deposit of carbon in the cylinder and improves the combustion, so that the exhaust is much less smoky. The use of water also makes possible a higher compression pressure, without the danger of preignition, and this tends to increase the efficiency of the engine.

The Jet Type of Carburetor

Practically the only type of carburetors used in this country at present can be classified under the head of *jet* carburetors. In this type of carburetor a jet of liquid fuel is injected, or drawn, into the current of moving air because air on its way to the cylinder on the suction stroke of the engine has a pressure less than the atmosphere. A small orifice, or nozzle, opening into the suction pipe delivers the liquid fuel into the moving air current, and by the mechanical action of this current the mist, or spray of liquid particles, is distributed through the air, which it saturates.

The four ruling factors in the determination of the quantity of liquid fuel which will flow through a carburetor jet orifice are as follows:

1. The viscosity of the fuel.
2. The temperature of the fuel.
3. The shape of the orifice or nozzle.
4. The effective head actuating at the orifice.

With reference to the first two, these bear a certain relation to one another, as the higher the temperature the lower will be the viscosity of the fuel, and the greater the volume which will flow through a small orifice in unit time. If radiation or conduction of heat is allowed to influence the fuel reservoir, an increase of fuel supply will result as the engine warms up.

If the fuel regulation is perfect before the engine is thoroughly warmed up, the mixture will be too rich in running; and, conversely, with a carburetor which is not adjustable, difficulties may be expected until the working temperatures are reached. Where efficiency is to be maintained at all times, a fuel adjustment which will be proportionately progressive from the minimum to the maximum opening of the fuel and air orifices is essential.

The carburetor jet has two functions to perform: (1) that of spraying the fuel into the mixing chamber; (2) that of regulating the amount of fuel passing through the carburetor in unit time. It is the duty of the jet to proportion the fuel supply to the air supply so that the mixture shall remain of constant composition at all times.

With low air velocities the action of the jet orifice becomes uncertain. There are two remedies for this difficulty. The first is to concentrate the air flow around the jet at low engine speeds, and the second is to provide a separate jet for slow running.

Varying speeds at varying loads are demanded with different fuels under different conditions of atmosphere and temperature; and these conditions cannot all be met successfully by an ordinary single-jet carburetor by reason of the principle upon which it works. The addition of spring-controlled extra-air devices to meet such conditions cannot produce correct results for modern demands. An attempt is sometimes made by such means to adjust the tension of the spring and the shape of the orifices so that the additional air admitted shall correct errors in fuel supply which creep in at high engine speeds. For all practical purposes, however, devices of this nature do not work well for any length of time.

The majority of multijet instruments have been provided with several orifices of different dimensions, working in choke tubes of different sizes, so that for various engine demands either one or the other or a combination of jets comes into action.

In the modern jet carburetor the level of the gasoline in the chamber which supplies the spraying jet is kept at a constant

level below that of the nozzle so that normally there will be no flow from the nozzle. The principal method of keeping the level constant is by means of a float and a needle valve. This device has been almost universally adopted in modern carburetors.

The carburetor used on nearly all multicylinder gasoline engines and on all automobile, aircraft, and marine motors is of the jet type in which the level in the small reservoir near the jet is kept constant by means of the float and needle valve. The float is made of sheet copper or cork.

The position of the float relative to the spray has resulted in two subtypes of carburetors. If the float is in a separate and distinct chamber, at one side of the jet, the carburetor is of the eccentric

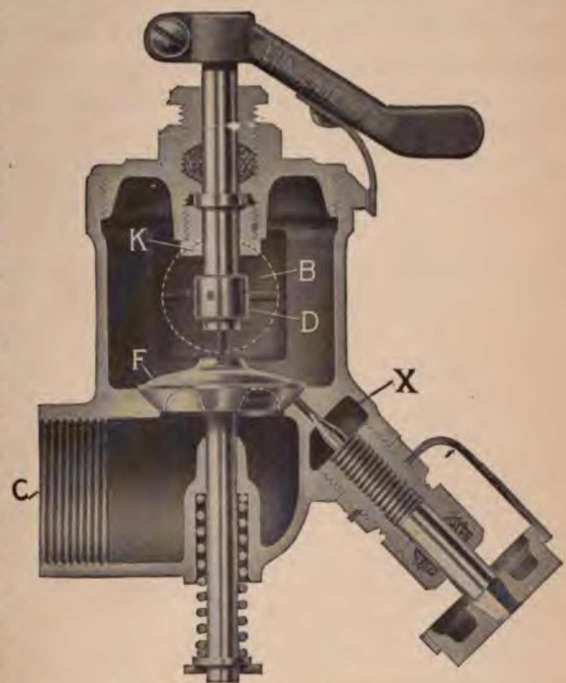


FIG. 18. The generator valve

type; but if the float chamber surrounds the jet and air passage, the carburetor is of the concentric type. The former is illustrated in the Zenith carburetor (Fig. 21) and the latter in the Model D Schebler carburetor (Fig. 19).

A simple form of carburetor known as the generator valve is shown in Fig. 18. The light disk F acting as a check valve is inserted in the air intake C and closes off the air and fuel as shown. During the suction stroke this valve is raised by

atmospheric pressure, and as the fuel outlet X is uncovered a jet of fuel spurts into the air as it passes on its way to the cylinder.

Generator valves of the type illustrated are designed for use on engines where extreme simplicity of control and ease of maintenance are desirable. Consequently they are especially adaptable to agricultural and innumerable other installations — stationary, marine, and portable — which do not demand that range of elasticity procurable from a highly efficient float-feed carburetor, and the proper functioning of which is dependent upon the correct adjustment and the maintenance of its more delicate mechanism. The two properties which recommend this valve for use on small engines are its low cost and its simplicity.

The Schebler Carburetor

The carburetor shown in Fig. 19 is of the concentric float type, the float being of cork, shown at F. The gasoline enters through the needle valve H, which is controlled by the float, keeping a constant level in the float chamber. Gasoline enters the air pipe through the nozzle D, which is slightly higher than the gasoline level. Air enters around the air valve A, passes down over the gasoline jet and out at R, whence it is piped to the cylinder. The throttle K is controlled by a rod attached at P. The air supply may be adjusted by the butterfly valve in the air inlet, and the gasoline by the lever E on the needle valve.

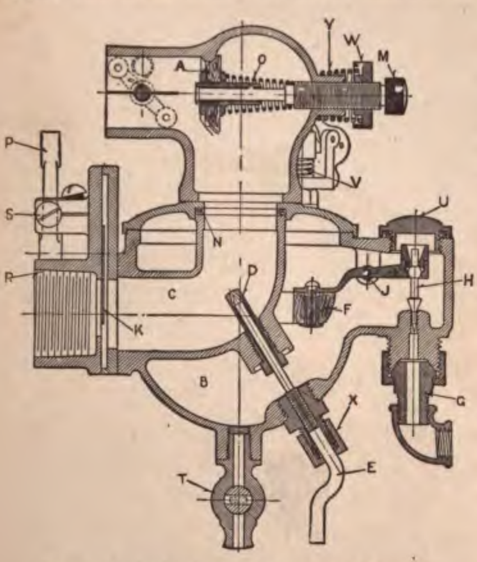


Fig. 19. Model D Schebler carburetor

The Model D is the original Schebler carburetor, simple of adjustment, and especially adapted for use on marine motors where extremely low throttling conditions are not required. It works in a very satisfactory manner and is easy to adjust, but has no particular claims from a scientific point of view. The principle of operation of this carburetor is the single fuel jet, with variable suction up to a certain point, when the spring-actuated air valve is allowed to open.

The fuel adjustments depend entirely upon throttle opening and have no relation to the demand of the engine at any time.

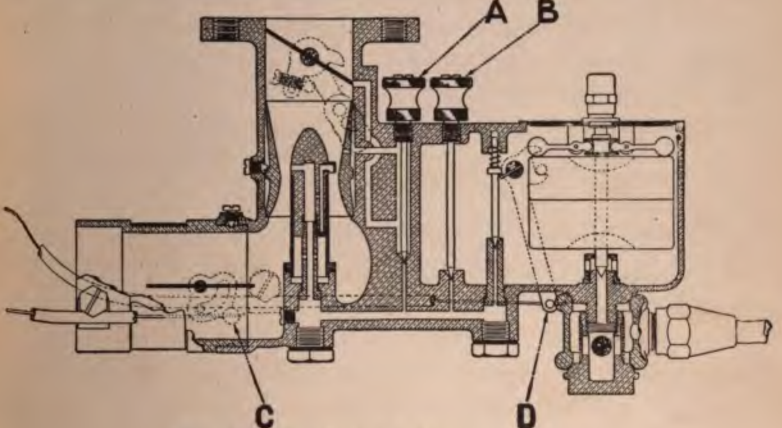


FIG. 20. Model A Schebler carburetor

It is therefore necessary to supply some sort of air regulator, and this is done by the adoption of the spring-actuated valve, through which the whole of the air passes. There is a distinction, however, between this carburetor and the older types of spring-controlled air-valve adjustments, in that extra air is admitted on the atmospheric side of the jet and not to the carbureted air stream between the jet and the throttle.

The Model D Schebler carburetor is at present used on all navy-type gasoline engines.

The new Schebler, Model A (Fig. 20), is of the eccentric float type and differs from all previous Schebler carburetors in

that two spraying jets, or nozzles, are used, one being the main jet located in the air passage, the other jet being higher up in the wall of the carburetor. The secondary jet is under the control of two needle valves, *A* and *B*, which must be adjusted by the engine operator. Valve *A* is provided for adjusting the idle or low speed, and valve *B* for adjusting the high speed of the engine.

Two dash adjustments, suitably connected to levers *C* and *D*, are provided for starting and warming up the motor. The adjustment secured by operating the lever *D* compensates for the flow rate of cold fuel without restricting the air supply, or, in other words, furnishes the necessary additional gasoline required to warm a cold motor. Lever *C* operates the starting shutter in the air intake, and is used for initial starting only. As soon as the engine is started the shutter should be immediately returned to the normal position shown.

The Zenith Carburetor

This carburetor is at present used on many motor cars and aircraft engines manufactured in this country. The design of this carburetor embodies the following essential features: carburetion is unaffected by the variation in throttle opening or in the speed of the engine; the engine should pick up quickly and start easily when cold; the carburetor must be free of moving parts. With regard to speed variation and throttle opening, other good designs of carburetors are also independent, but it is still a debated question as to whether a moving part, if simply constructed and not liable to suffer from wear, is a disadvantage or not.

The Zenith carburetor is built on the principle of the compound nozzle, which was invented by Baverey, a Frenchman, in 1906. Baverey's idea was to use a nozzle or jet which would supply a mixture growing richer in gasoline as the suction increased; and also one which would supply a mixture growing leaner under the same conditions; the two nozzles being so designed that one would counterbalance the fault of the other, thus giving a normal mixture from the combination of the two nozzles.

The Single-Jet Carburetor

To illustrate this principle briefly, let us consider the elementary type of carburetor, or mixing valve having but a single jet, as shown in Fig. 21. *X* is the passage through which the mixture is drawn into the engine on the suction stroke. *T* is the throttle of the butterfly type by means of which the amount of mixture drawn through *X* may be varied. *G* is a nozzle or jet set into *X* at its throat or point of least cross section. This part of the carburetor is also called the choke or Venturi. *G* is supplied with gasoline through the pipe *E* from the chamber *F*. The height of the gasoline in the chamber and jet is maintained at the level shown by means of a valve and float mechanism which shuts off the supply from the main tank when the gasoline has risen in the chamber to the predetermined level.

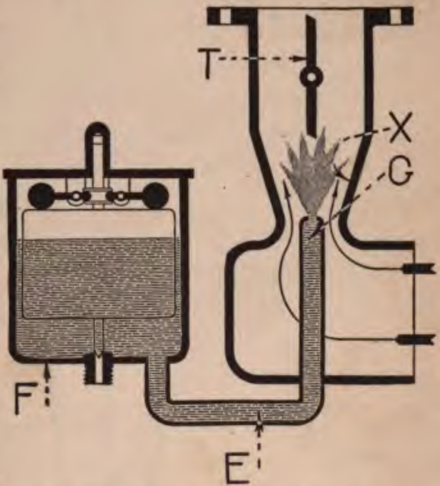


FIG 21. The single-jet carburetor

Successive suction strokes of the engine will produce a vacuum in the cylinders and intake manifolds which, with the throttle open, will cause a suction at the throat. This suction will act on both the air in the throat and the gasoline in the jet.

Assume that the throat and the jet have been so designed as to permit the passage of fifteen parts of air to one part of gasoline by weight under certain conditions of suction. A mixture of the proper proportions will then be drawn into the engine. It is natural to suppose that, as the speed of the engine increases, the flow of the air and the gasoline will increase in the same proportion. Such, however, is not the case. The law

of liquid flow states, in substance, that *the flow of gasoline from the jet increases under suction faster than the flow of air.* This gives a mixture that grows richer and richer, — a mixture containing a much higher percentage of gasoline at high suction than at low suction. In the simple type of carburetor illustrated, the ratio of fifteen to one of air and gasoline cannot be maintained constant under the varying conditions of suction, and such a carburetor will deliver a mixture containing a greater percentage of gasoline at high engine speed and full throttle opening than at low speed. Many different devices have been evolved for balancing or compensating this action of the single jet so as to secure a constant flow. One of the simplest and most satisfactory of these devices is the compound nozzle invented by Baverey and applied to the Zenith carburetors.

The Compensating Device

As an illustration of Baverey's principle let us consider Fig. 22. Here a fixed amount of gasoline, determined by the opening *I*, or compensator, is permitted to flow by gravity into the well of *J*, open to the atmosphere. The suction at jet *H* has no effect upon the flow through the compensator *I*, because the suction is destroyed by the open well *J*. As the motor suction increases (owing to an increase in speed or in throttle opening) more air is drawn up through the carburetor while the amount of gasoline remains the same, and therefore the mixture grows leaner and leaner. By combining this compensating device with the single jet we secure the compound nozzle giving us a constant flow.

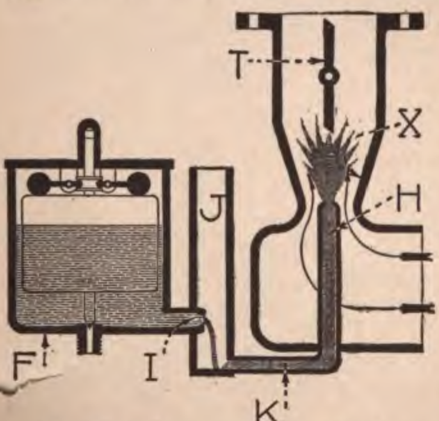


Fig. 22. The compensating device

THE COMPOUND NOZZLE

Fig. 23 shows the single jet *G* which is fed through the pipe *E*, compounded with the cap jet *H* fed by the compensator *I* through the open well *J*. The compound nozzle thus receives its gasoline from two sources. At any speed except idling speed, both sources of supply are in action. The main jet *G* (the one controlled by the suction) is selected of the proper size to give just about enough gasoline at high speed; at low speed or small throttle opening it will of course be quite deficient. This unavoidable defect of one nozzle, starting lean and growing richer until it is almost right at high suction, is compensated by the peculiarity of the other jet *H*, which also starts lean but keeps growing leaner. The compensator *I* lends its strong support to the main nozzle *G* at low suction when it is most needed, and withdraws it gradually as the nozzle *G* gathers in strength with increasing suction. One supplements the other so that at every engine speed there is a constant ratio of air and gasoline to stimulate efficient combustion.

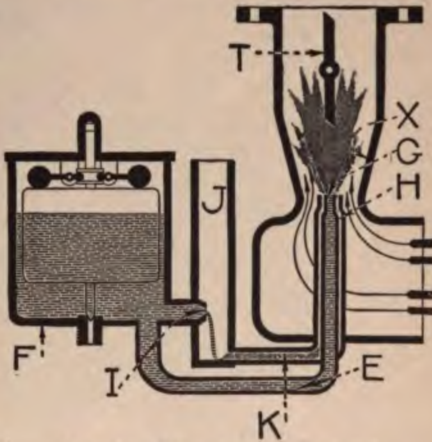


FIG. 23. The compound nozzle

IDLING DEVICE

At low speed, when the butterfly valve *T* is nearly closed, the main jet and cap jet give but little gasoline, but as there is considerable suction on the edge of the butterfly, the gasoline is drawn through the idling device, terminating in a priming hole *U* (Fig. 24). The gasoline is drawn by suction to the

priming hole, and, mixed with the air rushing by the butterfly gives an ideal slow-speed mixture. When the butterfly is opened

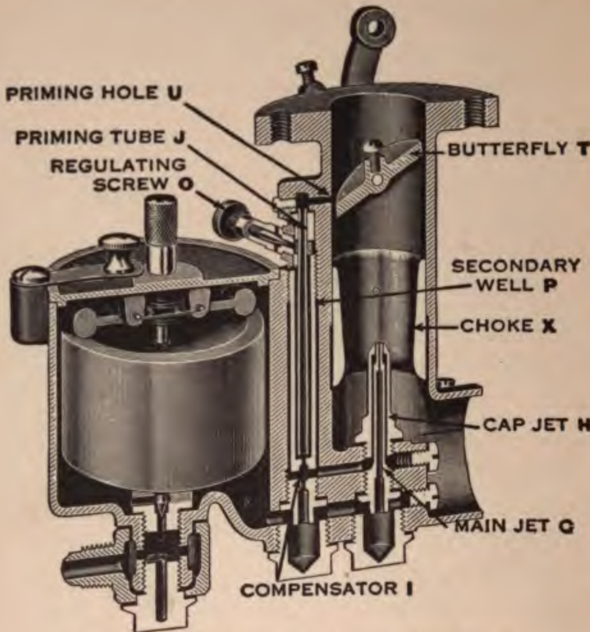


FIG. 24. The Zenith carburetor in section

further, the idling device ceases to operate because the increased flow picks up gasoline from the main jet G and cap jet H, thus cutting off the supply from the priming hole U.

ALTITUDE ADJUSTMENT

This device is incorporated in Zenith aëronautical carburetors for the purpose of adjusting the gasoline supply to the changed conditions met with in higher altitudes. A carburetor adjusted to deliver a properly proportioned mixture at sea level will supply an increasingly rich one as the machine mounts to higher altitudes, owing to the difference in temperature, density, and the quantity of oxygen in the air. The altitude adjustment consists of two screened air inlets connecting the top of the float chamber

with the open air. The well P is in open communication at its top with the float chamber. A passage is provided from the float chamber to the carbureting chamber below the throttle valve; this passage is fitted with a stopcock, which is manually operated from the pilot's seat. Under normal conditions, that is, on the ground, the stopcock is closed, and the gasoline in the float chamber is subjected to atmospheric pressure through the screened air inlets. When the engine is running, the partial vacuum produced in the throat, or choke, will draw the gasoline out of the main and cap jets in proper proportions. At an altitude of about 6000 feet, the aviator will begin to open the stopcock, thus drawing air from the float chamber and establishing therein a partial vacuum, which depends upon the amount of opening of the stopcock. This partial vacuum will impede the flow of gasoline through the jets, and the mixture will be made more lean.

The Stromberg Carburetor

The Stromberg carburetor, which is used on many motor cars, is of the eccentric float type. This carburetor is also one in which both the air and gasoline openings are fixed in size, and in which the gasoline is metered automatically, without the aid of moving parts, by the suction of air velocity past the jets.

The Air-Bled Jet

The Stromberg carburetor operates on the principle of introducing a small amount of air into the gasoline jet before it sprays into the main air passage, forming what is known as an *air-bled jet*. This air, taking the form of tiny bubbles, breaks up the gasoline discharge, frees it from the retarding action of surface tension at low suction, and regulates the gasoline flow so that it responds to the motor suction and, in accurate proportion, to the air flow. Thus the function of properly proportioning the mixture is performed with a single nozzle. Complete atomization is secured by the two Venturi tubes shown in Fig. 25.

The gasoline, leaving the float chamber past the point of t
high-speed adjusting needle (Fig. 25), rises through the verti

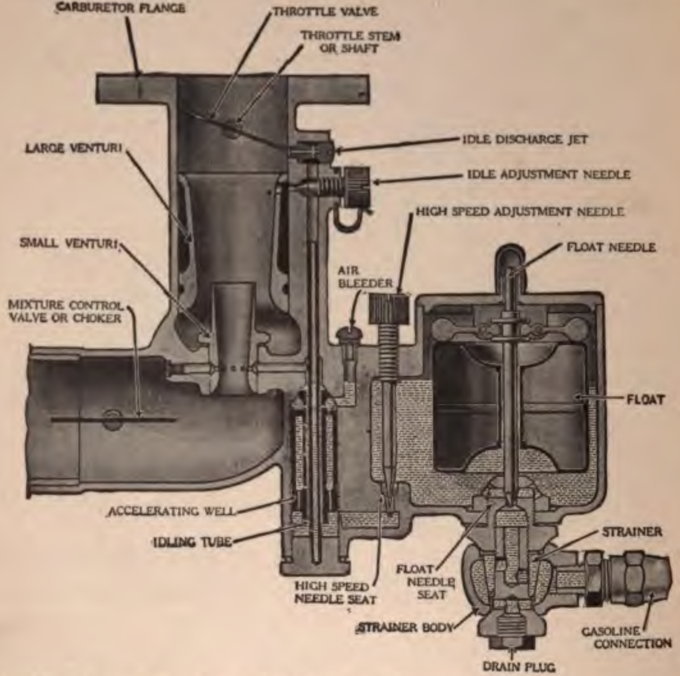


Fig. 25. The Stromberg plain tube carburetor (with motor at rest)

channel *B* (Fig. 26). Air taken in through the air bleeder, or protecting cap, *C* discharges into the gasoline channel through small holes *D*, breaking up the flow and producing a finely divided emulsion. This then issues forth through a number of jets into the high-velocity air streams of the small Venturi *E*. This construction gives a constant proportion of air to gasoline. The Venturis then atomize the fuel letely.

Fig. 26. Air-bled jet

The Accelerating Well

It is a well-known fact that economical and efficient mixture settings always seem to lag in response to the opening of the throttle and are also very susceptible to changes in temperature, while adjustments that are flexible show an increase in gasoline consumption. This is due to a relative lag of the heavier gasoline particles passing through the intake manifold to the cylinders, causing a temporary rush of air and a deficiency of gasoline just after the throttle is opened.

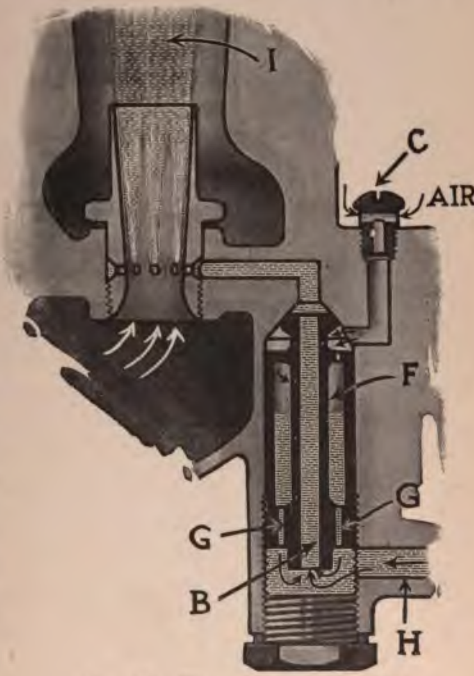


Fig. 27. The accelerating well

Good acceleration from an economical setting of the carburetor therefore requires a temporary enrichment of the mixture. With the accelerating well *F* (Fig. 27) the extra gasoline discharge is automatically governed by the suction of the motor, thus giving a prompt response to the throttle and a powerful acceleration to the motor.

With the motor idling or slowing down, the accelerating well *F* (Fig. 27) fills with gasoline; and whenever the Venturi suction is increased by opening the throttle or by increasing the engine speed, the level in the well goes down and the gasoline thus displaced passes through the holes *G* to join the flow from *H*, thus more than doubling the normal rate of feed entering the Venturi.

Idling Device

An idling device similar to the one used in the Zenith carburetor is used in the Stromberg. During idle or low-speed running the gasoline in this carburetor is carried up to the lip of the throttle, where it is discharged directly into the intake manifold in an extremely fine spray. The atomization of this low-speed supply is further assisted by dilution with air, the amount of which is governed by the adjusting screw *F* (Fig. 28), whose position controls the idling mixture.

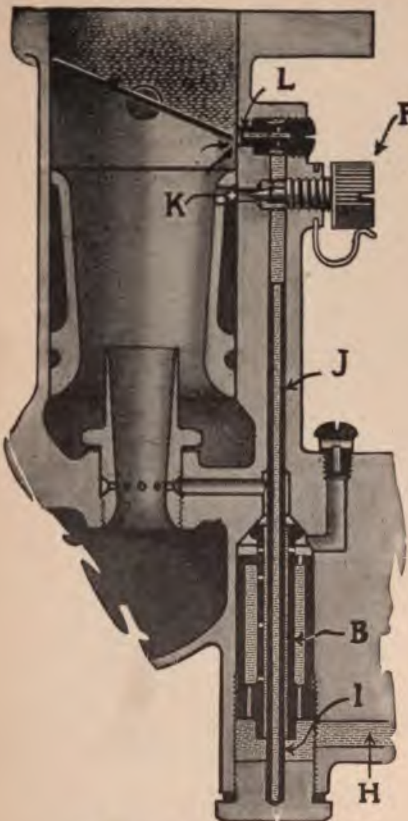


Fig. 28. The idling device

Referring to Fig. 28, in the center of passage *B* is located a tube *J*. When the throttle is closed, gasoline is drawn in through the hole *I*, mixed with air taken in at *K*, and discharged through the idling jet *L* with a high degree of atomization, owing to the fact that a high vacuum exists above the throttle when the motor is idling. The idling adjustment ceases to operate after the throttle is opened.

The Stromberg Aëroplane Carburetor

In Fig. 29 is shown a section of one type of aëroplane carburetor. This carburetor operates on the same principle as the one last described. The essential difference between the

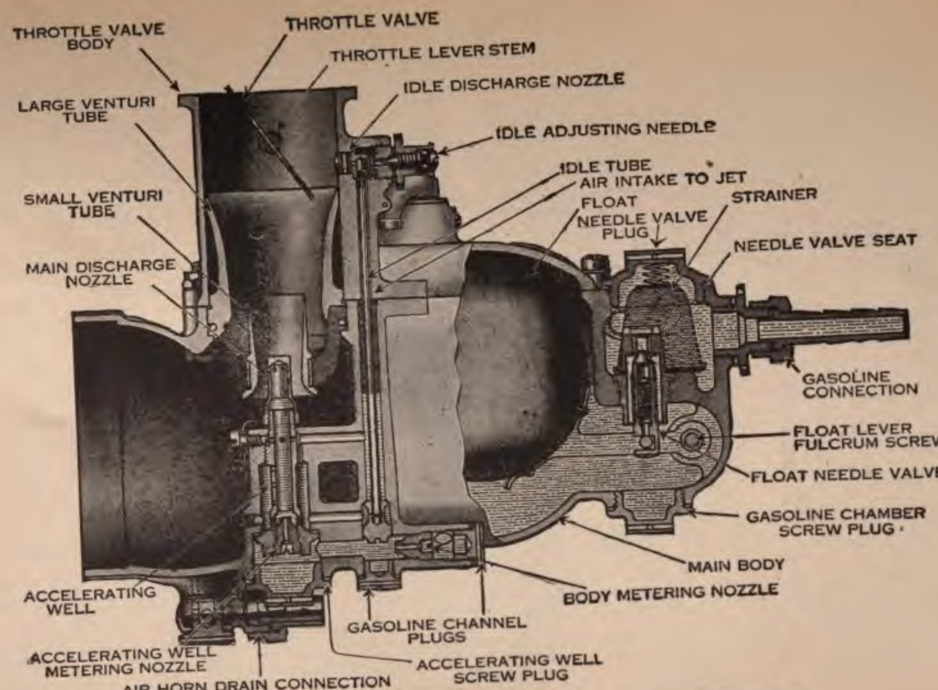


FIG. 29. Sectional view of Stromberg aëroplane carburetor

two models consists in the use of a special float chamber and float-valve action in the aëroplane carburetor. This is shown in Fig. 30. The float mechanism is positive in its action and hung in such a way that it will operate at angles between a 45-degree climb and a straight dive, also under considerable sidewise inclination. The float needle-valve is pointed upward so that any dirt will wash down, away from the valve seat, and is held to its pin by a self-contained spring plunger to obviate wear.

Float Action

With no fuel in the carburetor, the float drops down to the position shown by the dotted lines (Fig. 30), leaving the needle valve open. As fuel is admitted from the supply tank, entering

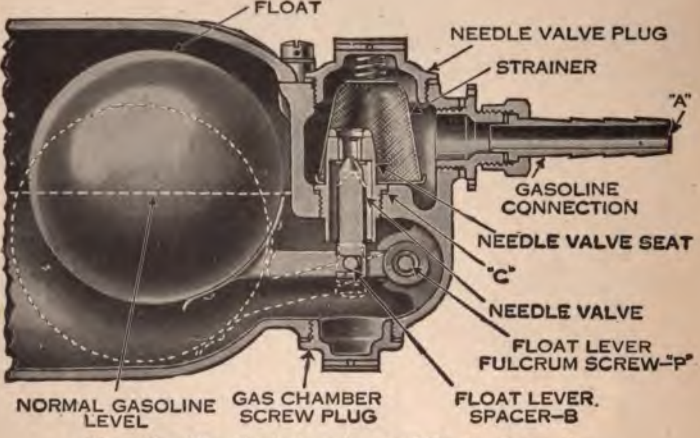


Fig. 30. The float chamber and float-valve action

the line at *A* and passing through the strainer before reaching the fuel orifice, the float rises and shuts the valve as the fuel reaches the level shown. When the motor is running and fuel is being drawn out of the float chamber to the jets, the valve does not alternately open and close, but takes an intermediate position such that the valve opening is just sufficient to keep the fuel supplied and the level constant. The running level is about one-eighth inch below the standing level.

Float Operation in Different Positions of the Plane

In airplane service it is necessary that this mechanism should operate positively at all angles and positions where power is demanded from the motor, and that it should not permit leakage

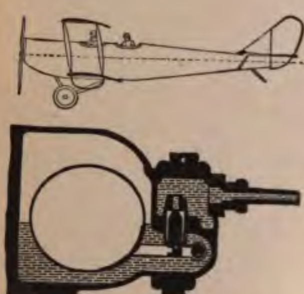


Fig. 31. Float action in horizontal flight

Fig. 32. Float action during a dive

of gasoline in other positions. The three views, Figs. 31, 32, 33, show the conditions in this carburetor in several different positions. During a dive, climb, or side-skid the action is normal, owing to the way the float is suspended. When the motor is stalled with the plane upside down, the float is no longer supported by the gasoline, and the valve shuts off, as shown in Fig. 33. To obtain these advantages the carburetor should be attached to the motor in such a way that the fulcrum *P* (Fig. 30) is toward the tail of the plane.

Fig. 33. Float action when fly-ing upside down

The operation of the float mechanism during the different aërial maneuvers depends not only upon gravity but also u

the motion of the airplane. If the position or motion of the plane is such that the pilot tends to fall away from his seat and be supported by the life belt, the same forces will cause the float to go up; that is, to close the needle valve. At this same time the fuel will go to the top of the float chamber and cease to flow from the discharge jets. The float and fuel will then occupy the position shown in Fig. 33.

The Stromberg aëroplane carburetors are fitted with an altitude adjustment which operates and is controlled in a manner similar to that fitted on the Zenith carburetor.

There are a large number of other good carburetors on the market, many of which are coming into prominence. Among these there are several operating on the principle of the multiple jet and furnishing the proper mixture at all speeds. Some of these carburetors are simple in construction, and when once properly regulated are remarkably free from adjustments.

Effects of Improper Carburetion

In the case of mixtures of gasoline and air, if the proportion of air to gasoline by weight exceeds about 22, or if the mixture is so rich in gasoline that this ratio is below 8, it will be impossible to obtain an explosion in the ordinary gasoline engine.

The principal effect of variations in composition of the explosive mixture is upon the rapidity of flame propagation. To impoverish the mixture by diminishing the proportion of fuel in it retards the ignition process, diminishes the initial pressure, lowers the mean effective pressure, and may be carried to the point at which ignition will not occur at all. An impoverished mixture, furthermore, and particularly one that is diluted with the products of combustion, may ignite so slowly that it is not completely burned at the time when the exhaust valves should open at the beginning of the return stroke. This state of affairs is particularly annoying with the 2-cycle type of engine, since the incoming fresh charge will be ignited prematurely, and usually this ignition will run back into the crankcase, causing a crankcase explosion which may result in injury

to the engine. In 4-cycle engines some of this lean mixture may still be burning when the intake valve opens on the next succeeding stroke. This results in irregular operation of the engine and will cause ignition of the gases in the intake manifold, resulting in a back-fire, with which all engine operators are familiar.

A rich mixture, which is indicated by a black smoke in the exhaust, is also slow burning, but it does not cause a back-fire. It does, however, cause irregular operation and overheating of the engine. The remedy is obviously to decrease the amount of fuel or increase the air supply. A bluish smoke in the exhaust is caused by the use of too much lubricating oil.

Carburetion at High Altitudes

Since the density of the atmosphere decreases as the altitude increases, the ordinary aircraft engine will develop power only in the ratio of the density of the air at a given altitude to that at ground level. This is due to the fact that the engine absorbs less weight of mixture at high altitudes than at low altitudes. At a height of 25,000 feet above sea level the horse power of an engine will be reduced about 50 per cent.

To maintain constant power delivery at high altitudes it is necessary to supply the carburetor with air under atmospheric pressure. This is accomplished by using a *supercharger* which compresses and heats the air before it is delivered to the carburetor. The supercharger is an air-compressor of the centrifugal type which may be connected directly to the engine shaft, or to a special turbine driven by the exhaust gases from the cylinders. The apparatus adds considerably to the weight of the power plant and furthermore absorbs about 10 per cent of the power of the main engine. These disadvantages are offset, however, by the recovery of as much as 40 per cent of the horse power at an altitude of 25,000 feet and a great increase in the flying speed.

CHAPTER VIII

IGNITION

It has already been stated that the problem of increasing the heat energy of the mixture of gas and air in the cylinder demanded that after the mass had been compressed it should be ignited. The fuel would then combine with the oxygen supplied with air and impart the increased pressure resulting from this heat to the piston. This ignition should be so timed as to occur at the proper point of the cycle so far as the gas is concerned, and at the proper point of stroke of the piston so far as the motor is concerned. In the Otto cycle this ignition should take place at such a point that the combustion will be complete, or nearly so, when the power stroke begins.

The time of ignition varies with conditions and cannot be set by any fixed rule. If electric ignition is used, the device is so arranged that the point of ignition can be varied at will between certain limits. In general the conditions that affect ignition are, first, the speed of the engine; second, the kind of fuel used; and, third, the quality of the mixture.

The higher the speed of the engine, the earlier should the spark be set. This is explained by the fact that it takes an appreciable time for combustion to occur after the spark is fired. At high speeds, then, the spark must be set early in order to have the maximum pressure occur at the beginning of the stroke. Some manufacturers make arrangements for advancing or retarding the spark automatically by a centrifugal governor, as the engine speeds up or slows down. The important advantage thus gained is that the firing spark always occurs when the armature of the magneto is in the maximum current position. As an engine slows down, owing to the increase of load, the period of time in which combustion may take place is lengthened;

and if the spark is advanced for high speed, it occurs too early for the reduced speed, and the maximum pressure is set up before the piston reaches dead center. This trouble makes itself known by a sharp knocking in the cylinder.

As some fuels burn more rapidly than others, these will then require a later spark than the slower-burning fuels; also, since a high compression increases the rate of combustion, the higher the compression the later may be the ignition for a given fuel.

When an engine is running with a lean mixture, combustion will be slower, and the ignition should be correspondingly earlier. A mixture that is too rich would require an early spark for the same reason. Perfect mixtures have the most rapid combustion and require the latest spark.

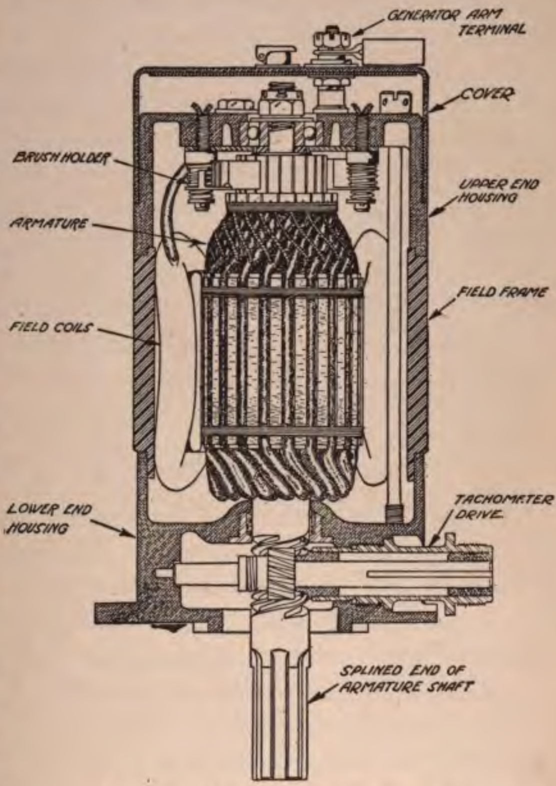


FIG. 34. Cross section of generator

There are three principal systems of ignition at the present time: (1) hot-tube ignition; (2) autoignition due to high compression; (3) electric ignition.

The first system is practically obsolete, but is still used in some small stationary gasoline engines and older forms of oil

engines. It is simple and certain, but timing can never be exact where a hot tube is used. The second system, of autoignition, is used in large Diesel engines. The third system, of electric ignition, is used on practically all gasoline engines being manufactured at the present time.

The modern electric ignition systems may be classified as the generator-battery and the high-tension magneto system.

In general the electric-ignition system consists of an electrical circuit of wire, or a combination of wire and the metal of the motor; a gap, or circuit-breaking device (spark-plug points), inside the cylinder; a commutator, or distributing device, outside the cylinder, and a source of electric current. Other devices used are a switch, induction coil, and condenser. The sources of electric current are a storage battery and some type of generator or magneto. Dry cells may also be used.

Generator-Battery Ignition System

The generator-battery ignition system used on the Liberty aircraft engine and many automobile and marine engines consists of a constant source of low-tension direct current supplied by a generator and storage battery. Each Liberty engine is equipped with standard generator-battery equipment consisting of:

1. Low-voltage direct-current generator.
2. Switch and voltage regulator.
3. Two distributor assemblies.
4. Storage battery.

These form a duplicate means of carrying on ignition in each cylinder of the engine.

The ordinary current furnished by a battery or generator is of too low voltage to jump across the gap of the spark plug. In order to raise the voltage of the battery or generator, an induction coil is incorporated in the system. This supplies the high-tension current necessary to jump the spark-plug gap.

The generator, shown in section in Fig. 34 and assembled in Fig. 35, is so arranged that the voltage is kept constant at all

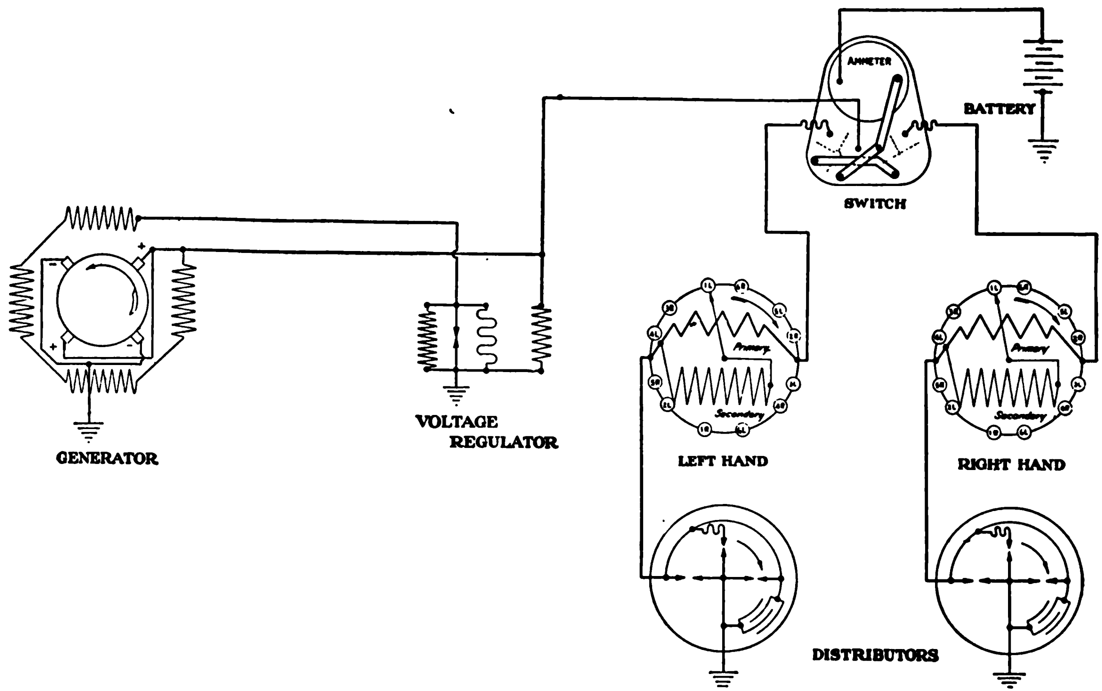
operating speeds. As the generator does not produce sufficient voltage at cranking or low idling speeds, the current at this time is supplied by the battery. In this way a practically constant pressure of low-tension current is available at all times. The battery is of special construction, light in weight, and will function satisfactorily in any position without leaking electrolyte. The capacity of the battery, when the generator is not in circuit, is sufficient to operate the 12-cylinder Liberty engine at flying speed for three hours with double ignition, or over eight hours with single ignition. The engine, after once being started, can be operated indefinitely without the battery if a speed of over 500 revolutions per minute is maintained. The battery remains in the circuit at all times to permit starting the engine and as an emergency source of supply in the event of damage to the generator or its circuit.

Fig. 35. Generator assembled

The generator is controlled by a voltage regulator (see Fig. 36) which prevents the output exceeding a predetermined figure. As the generator is supplying current direct to the ignition in regular operation, it is essential that the pressure of the current supplied shall not vary materially from low to high speed. It is by means of the voltage regulator that the pressure is kept constant after reaching a speed of 650 revolutions per minute, regardless of the variation in engine speed.

The regulator is a magnetically operated device controlling the amount of current flowing through the generator field circuit. Reducing or increasing the amount of current flowing through the field coil reduces or increases the amount of magnetic flux, with a corresponding decrease or increase in the voltage produced by the armature.

By means of the induction coil the low-tension current can be transformed to a high-tension current. The induction coil


AMMETER
BATTERY
SWITCH
Primary
Secondary
GENERATOR
VOLTAGE
REGULATOR
LEFT HAND
RIGHT HAND
DISTRIBUTORS

shown in the circuit diagram, Fig. 36, consists of a *primary* winding of comparatively few turns of insulated copper wire wound around and insulated from a soft-iron core. The current flowing around the core produces a strong magnetic field. The *secondary* winding, composed of many turns of fine copper wire, is wound over but insulated from the primary and terminates in a ground on one end and a high-tension button on the other end.

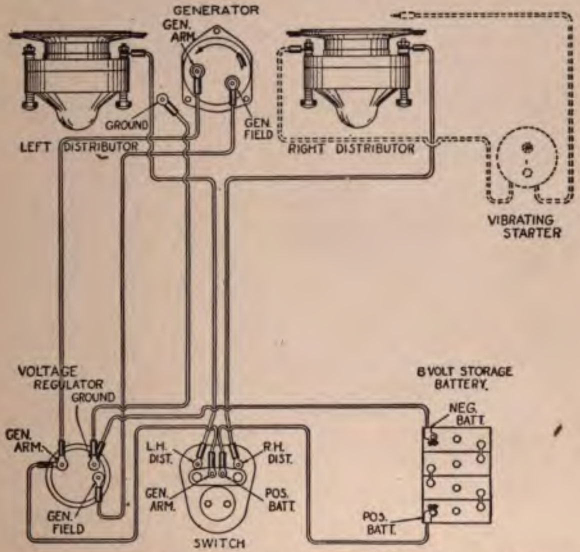


FIG. 37. Wiring diagram of Liberty engine ignition

When the current flowing in the primary winding is interrupted abruptly by means of a breaker mechanism, a high-tension current is induced in the secondary winding, owing to the rapid change effected in the magnetic field.

The induction coil is constructed and insulated to withstand the high voltage produced and is sealed moisture-proof in a molded bakelite case called the distributor head (illustrated in Fig. 38). This head also forms the cover for the breaker mechanism. The terminals of the coil are carried outside the head by means of permanent straps and thumb nuts which connect directly, without leads, with the breaker-mechanism circuits.

The breaker mechanism consists of contacts, operated by a cam, which open and close the circuit between the primary winding and ground, and provide the means of timing the occurrence of ignition with the position of the pistons.

Two contacts are located diametrically opposite and electrically in parallel, and are called the main contacts. These interrupt the primary current, producing ignition. Either contact alone is of sufficient capacity to carry on the operation properly and indefinitely. They are duplicated to insure operation in the event of the breakage of one spring or of one contact point. To reduce chattering, the main contact springs are cushioned with soft rubber blocks vulcanized to the contact arms. A third contact arm, called the auxiliary arm, is electrically in parallel with the main arms but also in series with a small resistance unit which limits the flow of current to this arm. This forms a safety device preventing the engine from operating in a reverse direction.

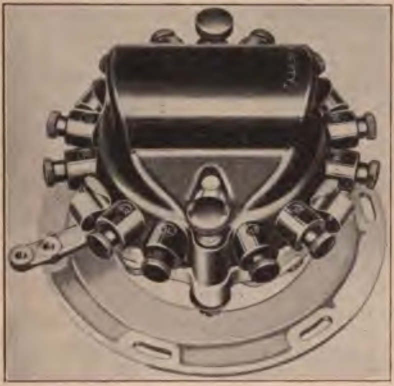


Fig. 38. The distributor head

In normal rotation (clockwise viewed from the distributor end) the auxiliary contact arms open a few degrees prior to the main contacts and cause no change in the amount of the current flowing through the induction coil. The main contacts, opening the circuit last and interrupting the flow of the current abruptly, cause a high-tension current to be induced in the coil.

Should the engine be turned in reverse direction, as when rocking it back and forth, the main contacts open first, leaving the auxiliary contacts closed and causing a reduction in the current flowing through the primary winding to an amount limited by the resistance unit in series with the auxiliary contact arm. This limits the current to such an extent that when the

auxiliary contact opens, the energy in the coil is reduced. The spark thus obtained from the secondary circuit will be too weak to produce ignition. The auxiliary contact, being closed when the main contacts open, also forms a short circuit for the condenser and prevents the induction of high-tension current.

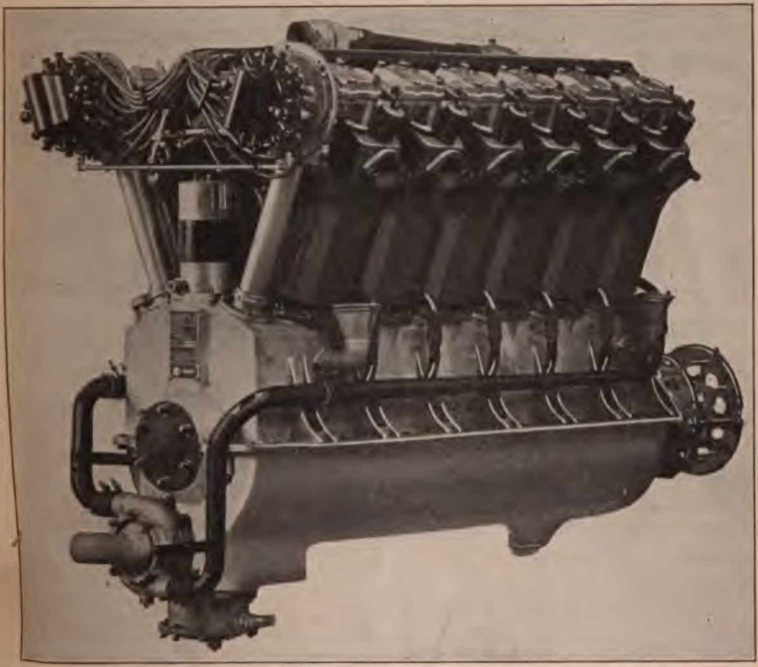


FIG. 39. Liberty engine showing generator, distributor heads, and cable leads of the ignition system

The low-tension current supplied by the battery or generator is controlled by means of a two-lever ignition-switch unit shown in Fig. 37. This unit also contains an ammeter, which at all times indicates the flow of current to or from the battery.

Advance and retard of spark are obtained by revolving the distributor breaker mechanism and head on its base. Ten degrees retard and thirty degrees advance are provided. Simultaneous movement of both distributors is obtained by connecting

them horizontally with a straight adjustable rod giving a simple, accurate control. This connecting rod may be seen in Fig. 39, which shows the Liberty aircraft engine completely assembled and equipped with the generator-battery ignition system. The generator, and the two distributor heads connected by insulated cables to the spark plugs, are plainly shown.

The ignition system above described will function efficiently at all speeds up to 2200 revolutions per minute of the engine. The normal maximum operating speed of the 12-cylinder Liberty engine in service is about 1750 revolutions per minute.

The High-Tension Magneto Ignition System

A magneto is a mechanical means for producing electric current. The high-tension magneto comprises within itself all the elements necessary for generating and intensifying the current, so that all that is needed to complete the ignition system are the spark plugs and the wires by which they are connected to the magneto. A battery is usually necessary for starting the engine.

The Bosch High-Tension Magneto

A circuit diagram of the Bosch high-tension magneto employed for 4-cylinder ignition is clearly shown in Fig. 40.

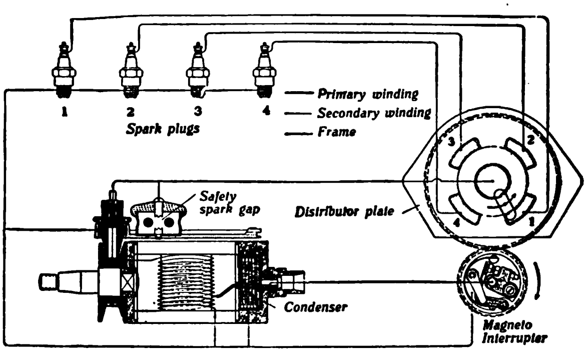


FIG. 40. Circuit diagram of Bosch magneto for 4-cylinder engine

The armature of this magneto is of the shuttle type, having a section roughly that of the letter H, wound with two coils of wire. One of these coils is of comparatively large wire and

corresponds to the primary circuit of an induction coil, while the other, which is of finer wire, acts as the secondary, or high-tension, circuit. The magnetic field is composed of two pairs of compound horseshoe magnets which are attached to pole pieces. These magnets also form the armature housing.

The rotation of the armature between the poles of the strong permanent magnets sets up, or induces, a current in the primary circuit in the armature and this is further augmented at regular intervals in the rotation of the armature shaft by the abrupt interruption of the primary circuit by means of the magneto interrupter. At the opening of the primary circuit the resulting discharge of the current from that circuit induces a current of much higher tension in the secondary circuit. The high-tension current thus created is collected by the slip ring on the armature and passed through the slip-ring brush, and then to the various distributor terminals, each of which is connected by cable to the spark plug in its respective cylinder.

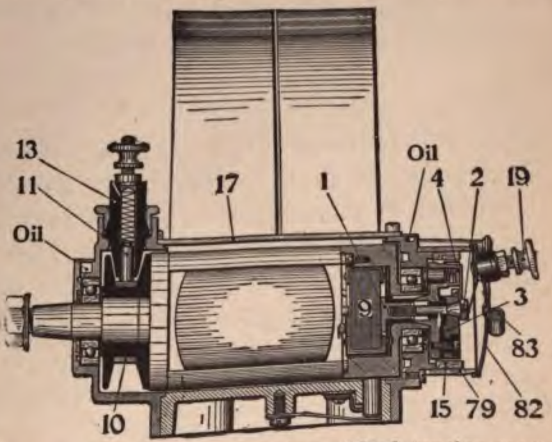


FIG. 41. Longitudinal section of high-tension magneto for a single-cylinder engine

1, brass plate for connecting the end of the primary winding; 2, fastening screw for magneto interrupter; 3, contact block on magneto interrupter; 4, magneto interrupter disk; 9, condenser; 10, slip ring; 11, carbon brush; 13, carbon holder; 15, steel segment; 17, dust cover; 19, nut for short-circuiting terminal; 79, timing control arm; 82, cover for interrupter housing; 83, flat spring for fastening the cover for interrupter housing

A condenser (see Fig. 41), is attached to the armature and in shunt with the contact points in the breaker box. It is made up of alternate layers of a conductor and a dielectric. Tin foil may be used for the former and mica or paraffin paper for the latter

At the moment of interruption of the primary current by the breaker points the current tends to keep on flowing and to jump across the air gap created by the separation of the breaker points. If this leakage were allowed to continue, the induced voltage would be lowered, the breaker points would become badly pitted owing to the arcking, and this condition would make it impossible to keep the points clean and in proper adjustment. The condenser, which is connected around the breaker points, overcomes these defects and insures better ignition.

Installation of Magneto

Since the magneto produces an ignition spark only at certain definite points in the rotation of its armature, it must be connected to the engine in such a manner that the spark is available always at the instant when required in the cylinder; that is, near the end of the compression stroke. The magneto, therefore, must be positively driven from the engine by a method of drive that will eliminate slipping. Belt or friction drive cannot be used, so recourse must be had to some form of gear or chain drive.

On a 4-cylinder, 4-cycle engine the magneto is driven at crankshaft speed and the arrangement of the contact breaker is such that the points separate twice during each revolution of the armature. A magneto for a 2-cylinder, 4-cycle engine would have but two distributor segments and would be driven at camshaft speed, which is equal to one half that of the crankshaft. A magneto for a 3-cylinder engine would have the segments spaced 120 degrees apart in the distributor and would turn at three-quarters crankshaft speed. On a 6-cylinder engine the distributor would have six segments spaced 60 degrees apart, and the armature would turn at one and one-half times the crankshaft speed. When used on the 2-cycle engines the armature speed would, of course, be doubled, since there are twice as many power strokes per revolution in the 2-cycle engine as in the 4-cycle.

Timing the Magneto

With the average 4-cycle or 2-cycle engine the proper operating results are obtained by timing the magneto as follows:

The crankshaft is rotated to bring the piston of No. 1 cylinder (the cylinder nearest the flywheel) exactly on top center of the compression stroke, and the piston is to be maintained in that position. The magneto is then to be secured to its bracket or bed on the engine, and the timing-control arm (see Fig. 41) on the interrupter housing placed in fully retarded position.

With that done, the magneto distributor plate should be removed by withdrawing the two holding screws (or depressing the two catch springs, as the case may be), thus exposing the distributor gear and brush. The cover of the interrupter housing is also to be removed to permit observation of the interrupter.

The armature should then be rotated by means of the exposed distributor gear in the direction in which it is to be driven, until the platinum interrupter contacts are just about to separate. The armature should be held in that position while the magneto drive is connected to the engine, due care being taken that the piston of No. 1 cylinder is still exactly on top center of the compression stroke. The operation is completed by replacing the interrupter-housing cover and distributor plate and connecting the cables between the magneto and spark plugs.

Timing Range

The interrupter housing is arranged so that it may be rotated through an angle of 35 degrees with respect to the armature shaft. The spark may be advanced by moving the interrupter housing, by means of the timing-control arm, in a direction opposite to the direction of rotation of the armature, and may be retarded by moving the interrupter housing in the same direction as the rotation of the armature. (The direction of armature rotation is indicated by an arrow at the driving end of the magneto.)

Dual Ignition

This system of ignition operates either on the magneto current or on battery current, according to the position of the switch.

The dual magneto is of the type above described and produces its own high-tension current, which is timed by the revolving interrupter. The parts of this interrupter are carried on a disk that is attached to the armature and revolves with it.

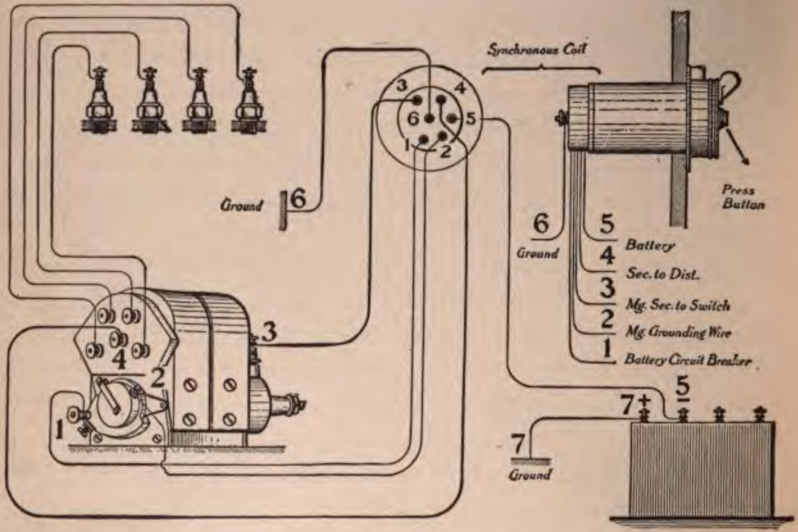


Fig. 42. Wiring diagram of the dual ignition system

The segments that serve as cams are supported on the interrupter housing. The magneto is also provided with a steel cam having two projections, this cam being built into the interrupter disk. The last-mentioned cam acts on a lever that is supported on the interrupter housing, the lever being so connected in the battery circuit that it serves as a timer to control the flow of battery current through the coil. The wiring diagram showing the connections for a 4-cylinder engine may be seen in Fig. 42.

It is obvious that the sparking current from the battery and from the magneto cannot both be led to the spark plugs at the

same time. This necessitates a further change from the independent magneto by removing the conducting bar between the collecting ring and the distributor. The collecting-ring brush is connected to the switch, and a second wire leads from the switch to the terminal that is centrally located on the distributor.

FIG. 43. High-tension magneto for 4-cylinder engine

When running on the magneto, the sparking current thus induced flows to the distributor by way of the switch contact. When running on the battery, the primary circuit of the magneto is grounded, and there is therefore no production of sparking current by the magneto. The sparking current then flows directly from the coil to the distributor connection.

The high-tension magneto, shown assembled in Fig. 43, is used on all navy-type engines. The same type of magneto is also used on many automobiles.

THE DIXIE HIGH-TENSION MAGNETO

This type of high-tension magneto is used on a great many aircraft and other engines. It operates on a principle entirely different from the rotating-shuttle type above described. The magnets and winding in the Dixie magneto are both *stationary*. The only rotating member is the pole structure shown in Fig. 44. The rotating member consists of two pieces of magnetic material, N and S, separated by a nonmagnetic (bronze) centerpiece B (Fig. 44). This member constitutes true rotating poles for the magnet and rotates in a field structure composed of two laminated field

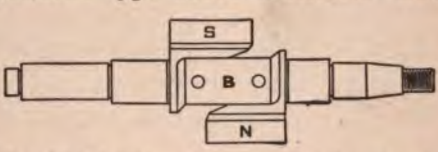


FIG. 44. Rotating element in Dixie magneto

pieces. The two pieces of magnetic material, *N* and *S*, rotating between the limbs of the magnets, form true extensions to the poles of the magnets and consequently are *always* of the *same* polarity. The ends of the wings are brought into contact with the poles of the magnets, as shown in Fig. 45, and therefore bear the same polarity of magnetism as the pole of the magnet *M* with which they are in contact. This polarity cannot change. It will be seen that there is therefore no reversal of magnetism through the wings of the rotating element, and consequently no eddy current or hysteresis losses.

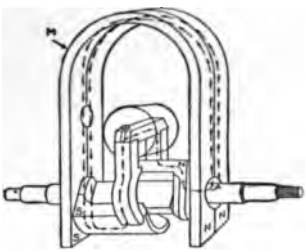


FIG. 45. The rotating element with the field structure and magnets

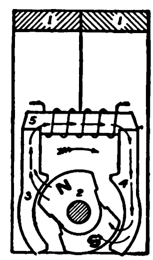


FIG. 46. Flux flowing in one direction through core 5

The rotor is surrounded by a field structure, as shown, which carries laminated pole extensions, on which the winding with its laminated core is mounted. As the rotor revolves, it causes the flux lines to be twisted about, so that the magnetism flows back and forth through the core of the winding, first in one direction and then in the other, according to the position of the rotor in relation to the poles of the field structure.

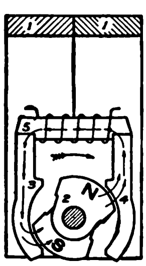
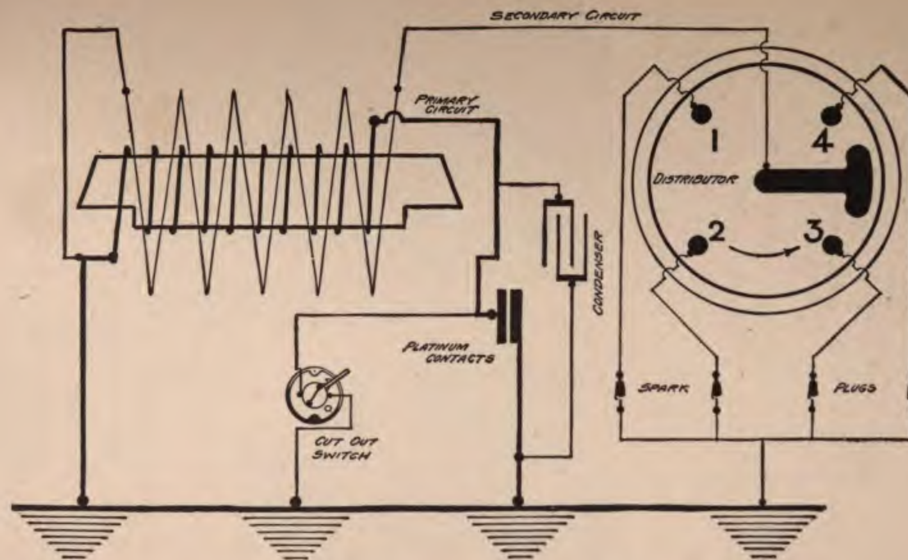


Fig. 47. Flux flowing in reverse direction through core 5

In a position at right angles to the rotating poles is the field structure consisting of the laminated pole pieces (3 and 4, Fig. 46) supporting the laminated core 5 which carries the winding. In the same figure the flux is shown flowing in one direction through the core 5. When the wing end is opposite 3, the flux flows to 3 and through 5 to 4, then back to wing *S*, of opposite polarity, thus completing the magnetic circuit.



Common ground or framework of magneto and engine

FIG. 48. Wiring diagram of Dixie magneto circuits

In Fig. 47, flux is shown flowing in reverse direction through core 5. The pole N having moved over to 4, the direction of the flow of flux is reversed; it now flows from 4 through 5 to 3, but the direction of flow in the wings is unchanged. It is thus obvious that the laminated core of high-tension winding must reverse its magnetic polarity. It is first saturated with magnetism flowing in one direction, as in Fig. 46. In Fig. 47 the direction is reversed. This reversal must take place at each half-revolution of the shaft.

The rotary pole structure may be equipped with two additional extensions of the north pole, and two of the south pole,

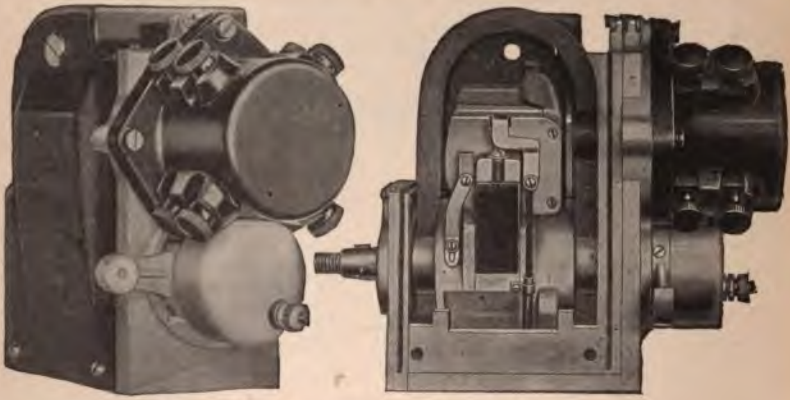


FIG. 49. Dixie magneto for 8-cylinder engine

arranged alternately, giving four (instead of two) reversals of flux through the core of the windings for every revolution of the rotary pole structure.

In addition to the magnets, a rotor, the field structure, and the winding, this type of magneto also is supplied with an interrupter, a condenser, and a distributor, which perform the same functions as these elements do in other high-tension magnetos.

In Fig. 48 is shown the wiring diagram of Dixie magneto circuits for a 4-cylinder engine, and in Fig. 49 are shown the front and side views of a Dixie magneto complete for 8-cylinder engines.

In addition to the two distinct types of high-tension magnetos above described there are several other excellent magnetos on the market. These are of the rotary-shuttle type and in principle similar to the one first described.

With all high-tension systems of ignition a storage battery is usually necessary for starting the engine.

Low-Tension Magnetos

A low-tension magneto is a simple direct-current or alternating-current generator. This type of magneto is used in connection with the low-tension system of electric ignition described at the end of this chapter. The magneto consists chiefly of magnets screwed to two pole pieces, a base, and an armature hung between the pole pieces. It is operated by gearing from off the camshaft drive. The shaft of the armature is insulated, and there are the usual brushes connected to the firing circuit. A washer fixed on the armature shaft is marked for timing. There is nothing inside the magneto that requires adjustment.

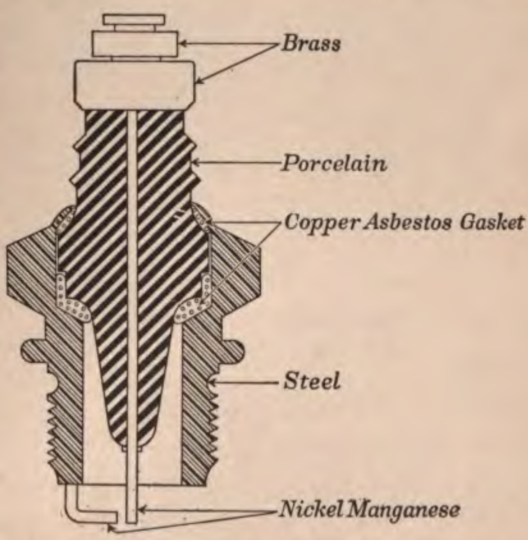


Fig. 50. One-piece spark plug with porcelain insulator

Spark Plugs

A very important item in all systems of high-tension electric ignition is the spark plug. The spark plug is made up of a central metal rod (electrode) surrounded by a thick tube of insulating material, which in turn fits into a

hollow metal plug threaded on the outside so as to screw into a threaded hole made in the cylinder for this purpose.

The insulating material is of specially manufactured porcelain; or of mica composed of a large number of compressed and consolidated disks, or of thin sheets of mica wound laterally around the electrode. Steatite, an artificial stone, and glass are also used for this purpose. The expansion of the several parts of the plugs must be adequately provided for. The insulator usually terminates some little distance back from the spark gap, thus preventing failure of ignition through accumulations of oil and soot.

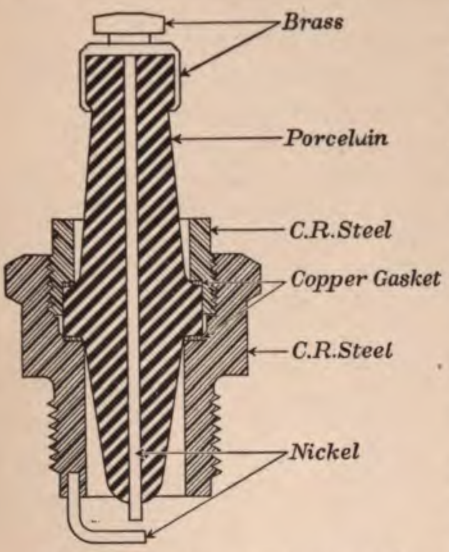


FIG. 51. Two-piece spark plug with porcelain insulator

In general practice a small wire is fastened to the outer shell of the plug and brought near to the end of the central electrode. The gap thus left is called the *spark gap*. Its width is between .020 and .032 inch.

The essential characteristics of a suitable spark plug are as follows: (1) it must be so constructed that it will withstand intense heat as well as sudden changes of temperature; (2) it must be proof against compression leakage; (3) the insulator must be able to withstand a high voltage; (4) the spark plug must be so constructed that it can be readily cleaned without injury; (5) it must be constructed of material that is not liable to injury by vibration or shock; and (6) the electrodes must be of such metal as will resist corrosion, and of a design that will tend to operate, irrespective of the effects of excessive oiling and sooting.

In connection with the electrodes for spark plugs, probably the best material in use is an alloy consisting of from 98.5 to 97.5 per cent of nickel and from 1.5 to 2.5 per cent of manganese. This material has been found by tests to resist the corrosion due to the oxidizing and reducing action of the gases present in the cylinder of an internal-combustion engine. Other materials used for electrodes of spark plugs are pure nickel, Monel metal, and nichrome (an alloy of nickel and chromium).

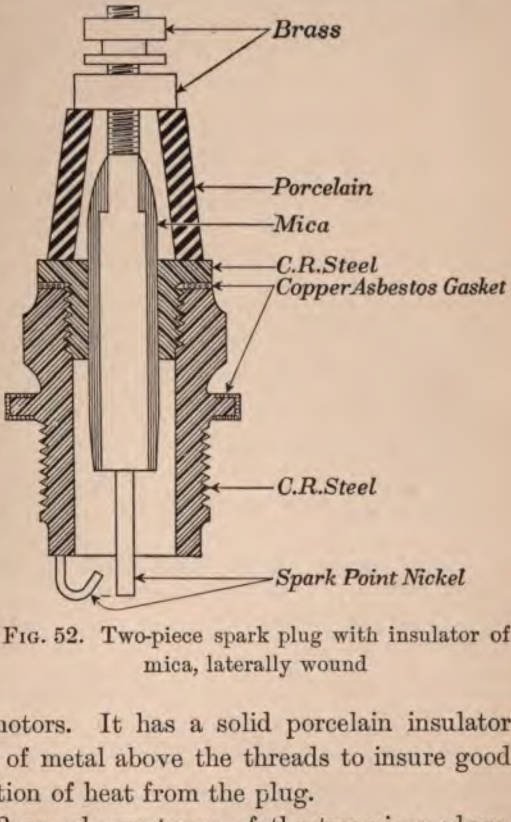


FIG. 52. Two-piece spark plug with insulator of mica, laterally wound

Spark plugs are classified as the one-piece plug and the two-piece plug. The latter type is more readily cleaned but is liable to compression leakage, owing to the extra joint necessary in this construction.

In Fig. 50 there is clearly shown, in section, a one-piece plug used on navy motors. It has a solid porcelain insulator and a sufficient body of metal above the threads to insure good conduction and radiation of heat from the plug.

In Figs. 51 and 52 are shown types of the two-piece plugs, the former having a solid porcelain insulator and the latter an insulator of mica, wound laterally, with a porcelain jacket. Cold-rolled steel is used for the body of the plug. Soft copper gaskets are used to make gas-tight joints between the two parts.

The correct position of the spark-plug electrodes within the cylinder is an important consideration, and the successful operation of the engine depends to a great extent upon the correct fitting of a spark plug. The best results are obtained when the firing points are surrounded by fresh gaseous mixture, as shown in Fig. 53.

Fig. 53. Correct position of spark plug in cylinder

If there is a recess between the firing points and the top of the cylinder, as shown in Fig. 54, a pocket is formed for burned gas; this permits carbon to accumulate rapidly, causing the plug to misfire.

The Use of Two Spark Plugs per Cylinder

Ordinarily combustion of the charge is sufficiently rapid with a single spark plug, so that the proper explosion is obtained at moderate engine speed. With high-speed engines, however, it has been found that more power may be obtained by igniting the mixture at two different points instead of one. This is accomplished by using two spark plugs per cylinder. When the two plugs are regularly used it is necessary, in order that the sparks shall occur simultaneously at both plugs, that they be connected electrically in series.

Fig. 54. Incorrect method of fitting spark plug in cylinder

The beneficial effect of using double ignition, as it is called, is due, no doubt, to the more rapid flame propagation obtained, for the time of attainment of the maximum pressure from the moment that the spark occurs depends upon the length of the maximum path of travel of the combustion wave. This path is shortened by employing two spark plugs suitably placed. Nearly all aircraft and racing engines are fitted with double ignition.

Firing Order of Cylinders

There are two possible firing orders, or methods of timing, for 4-cylinder motors, 1–2–4–3 and 1–3–4–2, neither of which has any appreciable advantage over the other. With 6-cylinder motors there are six possible firing orders; and if the cylinders are cast in pairs, and the exhaust passages of the cylinders in each pair are "siamesed," or come close to the cylinders, it is found advantageous to choose one of the following orders, in which the two cylinders of any pair never fire in direct succession: 1–5–3–6–2–4, 1–4–2–6–3–5, 1–3–2–6–4–5.

The surest way to prevent interference with the exhausts from the succeeding cylinders is to provide two exhaust manifolds, one for the three forward and the other for the three rear cylinders, connecting with a double exhaust pipe leading to the muffler.

With aircraft engines where crankshafts turn counterclockwise (looked at from the front) one of the two following firing orders is generally used for 8-cylinder V-type engines: 1L–4R–2L–3R–4L–1R–3L–2R; 1L–4R–3L–2R–4L–1R–2L–3R.

In the 12-cylinder V-type engines there are three desirable firing orders: 1L–6R–5L–2R–3L–4R–6L–1R–2L–5R–4L–3R; 1L–6R–4L–3R–2L–5R–6L–1R–3L–4R–5L–2R; 1L–6R–3L–4R–2L–5R–6L–1R–4L–3R–5L–2R. The first of these firing orders is the one used in the 12-cylinder Liberty engine. In the above firing orders No. 1 is the forward cylinder in each case. "R" and "L" refer to right and left, respectively.

The Low-Tension System of Electric Ignition

In addition to the high-tension electric systems above described, there is still one other system of electric ignition called the low-tension or the make-and-break system. This system is electrically simple but mechanically somewhat complicated. It is used mostly on slow-running gas and gasoline engines. Spark plugs are not needed in this system. The current supplied may be either direct or alternating.

The low-tension system of ignition depends upon the fact that a break in the flow of a primary electric current will cause an arc or spark across the broken ends. If such a break can be made inside the cylinder, so that the spark when formed is surrounded by the explosive mixture, the spark will ignite the mixture and explosion will take place.

The low-tension system of ignition consists in causing, by mechanical means, two points, or electrodes, located in the compression space to close and then open the electric circuit. This may be accomplished by causing the points to rub together and then separate, producing what is known as the *wipe spark*; or by forcing the points together and causing them to separate by means of a spring, sometimes called the *hammer break*. When the points break contact, a very hot spark is produced, because the inertia of the electric current produces momentarily a very high voltage.

For slow-running engines this system is very satisfactory and simple. The points of the electrodes in the cylinder are subject to much wear, however, especially with the wipe spark, and consequently they deteriorate very rapidly. The destructive action at the points may be reduced by placing a condenser electrically in parallel with the igniter points.

CHAPTER IX

LUBRICATION

Internal-combustion engines are without doubt the most difficult to lubricate of all known mechanisms. This is due to the unavoidable, inherent necessity of exposing the lubricated cylinders and pistons to extremely high temperatures.

The need for lubrication has its origin in the evidence of friction. By definition, friction is a loss of power or energy occasioned by the rubbing of one body or surface over another. It is the resistance to relative motion of surfaces in contact, and depends upon the nature and roughness of the surfaces. Friction is the conversion of useful energy into useless heat, accompanied by wear, and it can never be entirely eliminated in any mechanism. By making use of suitable lubricants properly applied, it can, however, be reduced to a minimum.

Lubrication, by definition, is the introduction of a smooth fluid or semifluid substance, such as oil or grease, between two moving surfaces to prevent them from coming into direct metallic contact. All bearing surfaces, however smooth to the naked eye or touch, are microscopically rough; and unless some medium is introduced which will cover and fill up these depressions, the surfaces will interlock and give rise to friction, heat, and rapid wear.

The fundamental theory of lubrication is that there should be a continuous film of oil between the rubbing surfaces of a properly lubricated bearing. When the moving parts are thus separated by a film of oil, the friction then takes place within the liquid itself, and between its particles and the surfaces in contact with it. The oil film thus prevents actual metallic contact, with its consequent risk of abrasion and seizing.

In an internal-combustion engine the oil film, in addition to reducing friction, must form a seal between the piston rings

and cylinder walls, to prevent the leakage past them of the gasoline vapor or mixture. For this purpose well-refined mineral oils of high flash point and well-maintained high viscosity are most suitable. In all lubrication the matter of correct viscosity is of prime importance.

VISCOSITY

The viscosity of an oil may be defined as its fluid resistance to flow, and is expressed as the number of seconds required for a definite volume of oil, under an arbitrary head, to flow through a standardized orifice at constant temperature. In other words, the viscosity is an empirical expression of the internal molecular cohesion (internal friction) of fluids. Readings are commonly taken at 100° and 212° F. In the United States the viscosity is generally expressed, in terms of the standard Saybolt viscosimeter, as so many seconds at 100° F.

All lubricating oils are blended oils; that is, oils of different viscosities are mixed to form one of the desired viscosity. In general, viscosity is the determining factor in the choice of oil for any engine, assuming the oil to be clean and free from grit and acids.

Oil manufacturers generally express the viscosity of an oil in the manner indicated above; but by the consumer it is expressed more roughly as light, medium, heavy, extra-heavy, etc., — as these terms are more generally understood. A light oil has a viscosity of from 180 to 250 seconds; a medium oil has a viscosity of from 250 to 350 seconds; heavy oils have a viscosity ranging between 350 and 450 seconds; extra-heavy oils run from 450 to 1500 seconds; and extremely heavy oils have viscosities of from 1500 to 2300 seconds, — all expressed in seconds Saybolt at 100° F.

When oils lighter than 180 seconds are used, the horse power of the engine falls very rapidly, until the pistons and bearings finally seize with oil of approximately 100 seconds. When oil is too light to maintain the proper protective film, the surfaces of the moving parts come into direct metallic contact, thus causing such great friction as to score, or even fuse, the bearing

surfaces. The use of extremely heavy or extremely light oils should be carefully avoided by all engine operators.

It has been found that with an engine in good condition mechanically, the fuel consumption reaches its minimum when a light oil of about 180 seconds is used. As the viscosity increases above 180 seconds the fuel consumption increases slightly but uniformly with it.

Between the range of light oils and the extra-heavy oils it is evident that there must be some viscosity where the highest economy of both oil and fuel is attained together with high horse power. Various tests have demonstrated that this point lies between 300 and 800 seconds, and that it depends upon the condition of the engines in which the oils are used and upon their average operating temperature. If it were not for the difficulty of a more rapid carbonization when heavy oils are used, no oil having a viscosity of less than 300 would be recommended by engine manufacturers; but since a practical compromise must be reached, light and medium oils (from 180 to 300 seconds) are regularly specified as being the most fool-proof in character, and hence best capable of meeting the widely differing conditions of service.

It has already been stated that an oil for internal-combustion engines, in addition to lubricating the rubbing surfaces, must form a seal between the piston rings and cylinder walls to prevent leakage past them. As the engine becomes worn and clearances increase, the viscosity of the oil used should be increased progressively, so as to maintain this seal intact. A heavy oil will give a thicker lubricating film and seal, and, owing to its better cushioning properties, will reduce the vibration that occurs in an engine after the bearings wear down.

In some engines where the clearance between the piston and cylinder is large by design, owing to the use of two different materials having great differences in their coefficients of expansion, such as aluminum and steel, it becomes necessary to use an extra-heavy oil to maintain a good seal. This condition is found in many aircraft engines where special oils are needed.

Temperature has a marked effect on the viscosity of an oil. The viscosity decreases rapidly with an increase of temperature and at the working temperature of high-speed engines even the extra-heavy oils have their viscosities reduced to about that of a light oil at its normal working temperature.

Lubricating oil readily absorbs any gasoline which may leak past the piston walls. A very small amount of gasoline greatly reduces the viscosity of an oil. For example, 5 per cent of gasoline absorbed by a lubricating oil may reduce the viscosity of the oil from 30 to 50 per cent of the original amount. Sufficient piston rings must be provided in each piston to achieve the requisite degree of gas-tightness under all running conditions, for the effect of leakage here is most detrimental to the efficiency of the lubrication and of the engine performance as a whole.

Oxidation

If it were not for the destructive effect that heat has upon lubricating oils, they could be used almost indefinitely. But heat is the greatest enemy of hydrocarbon oils, causing the destruction of their requisite properties. The degree of decomposition due to heat which occurs in service during a given period is determined by the relative heat-resisting properties of the oil; that is, its resistance to the formation of nonlubricating products by chemical change.

Regardless of the type of lubricating system employed in internal-combustion engines, oil is splashed at every stroke against the underside of the highly heated piston heads. This oil spray cools the piston to some extent, but the heat absorbed by the oil causes a decomposition to take place in it. In this manner the oil within the sump is turned black, and a solid black sediment is deposited.

The best lubricants show the greatest resistance to such decomposition, and they consequently precipitate the least amount of sediment. Even the highest grade of oil obtainable will deposit some sediment when used. This sediment deteriorates the good

oil remaining and thereby decreases the lubricating value of all the oil circulating through the bearings.

The analysis of crankcase sediment shows that it consists chiefly of solid or semisolid hydrocarbons (oxidation products) mixed with finely divided metal dust worn from the bearings. Experiments relative to oxidation of oil have established the fact that the presence of metal dust or metal oxides greatly accelerates the rate of sediment formation in lubricating oils when heated. For this reason one of the most vital precautions to be taken when running-in new engines is to frequently cleanse the crankcase of used oil which is contaminated with metallic particles and to refill it with fresh oil. Otherwise serious damage may result to the engine.

The Flash Point

The flash point of an oil is the lowest temperature at which the vapors arising therefrom ignite, without setting fire to the oil itself, when a small test flame is quickly approached close to its surface in a test cup. A suitable flash point is from 350° F. to 500° F. by open-cup test. On account of their higher operating temperature air-cooled motors usually require a higher flash point than water-cooled motors.

The Cold Test

This test is made to determine the temperature at which the oil congeals. Little difficulty is experienced in choosing an oil which will suit the lower temperatures at which the engine is operated. Recognizing the demands of services in northern countries, where cold climates prevail, oil refiners market low cold-test or "zero" oils to meet such special low-temperature conditions. The cold test of lubricating oils made from Gulf Coast or California crude oils is by nature low, since these oils contain little or none of the paraffin wax which causes the oil to congeal.

Volatility

All engine operators are familiar with both the odor and the appearance of oil vapors escaping from the crankcase of the engine through the "breather" pipes. The harder an engine is worked the more evident this loss of oil by vaporization becomes. If a lubricating oil contains a large portion of low-boiling-point constituents, the loss of oil vapors will be proportionately high when it is used in an engine, and vice versa. Some loss will always occur, but the choice of the correct oil will reduce such needless waste to a minimum and be a guaranty of a reasonably low specific consumption, good lubrication, and practically carbon-free conditions within the cylinder. The degree of volatility which lubricating oils should have is entirely determined by the maximum operating temperature of the engine and by the character of its load, whether full or variable. From this, it follows that the correct volatility of lubricating oils is a matter of great consequence if satisfactory economy is to be obtained in service.

Oils intended for use in engines that operate continuously at approximately full load and at high temperatures, such as aircraft engines, should contain a minimum quantity of low-boiling-point constitutents. On the other hand, passing from such conditions of high operating temperatures to those of widely varying and comparatively low operating temperatures, such as obtain in marine engines, pleasure cars, and trucks, it is necessary to increase materially the quantity of low-boiling-point constituents, to prevent serious carbonization. There is a limit to the addition of low-boiling-point fractions, for the reason that too large a quantity will increase the specific consumption of the oil in service; hence some mean value must be fixed upon, a permissible balance being struck between rapid carbonization and a high consumption.

Carbonization of Engines

The rapid carbonization of engine cylinders, etc. invariably results from the use of poorly refined oils of inferior quality. Carbonization of the combustion chambers, valves, and piston heads is caused also by the use of oils of incorrect viscosity (too light or too heavy), incorrect volatility, too high an oil level in the crankcase, or the presence of mechanical defects in the motor.

Carbon deposits, popularly called carbon, are in reality not all carbon, but contain percentages varying from 5 per cent to 75 per cent of that element. The remainder of the deposit consists of variable percentages of metal oxides and inactive earthy matter (road dust) and solid black carbonaceous or asphaltic compounds, according to the oil used. In marine motors salt is a common constituent. This fact is easily demonstrated by putting a small amount of carbon deposit scraped from the engine into a test tube and treating it successively with gasoline and carbon disulphide. These liquids dissolve the carbonaceous matter and leave behind only the free carbon and other insoluble matter.

One of the most serious mechanical defects contributing to the immediate carbonization of any engine in which it exists is the piston-ring leakage previously mentioned. The effect of this leakage is to destroy the oil seal existing between piston and cylinder and to decrease the compression and power. With leaky rings a surplus of oil is drawn into the cylinder during the inlet stroke. During the compression within the cylinder, part of the mixture of air and fuel is forced past the pistons into the crankcase, where it contaminates the oil. During the expansion stroke, the highly heated gaseous products of combustion escape past the piston rings and into the crankcase. The water vapor contained in these burned gases condenses and settles to the bottom of the oil sump, there forming an emulsion.

Carbon deposit on the combustion-chamber walls takes up an appreciable amount of space and consequently decreases proportionately the volume of the compression space. Owing to the

peculiar properties of gasoline-air mixtures this space can only be diminished a certain amount, or compression temperatures will cause premature, spontaneous ignition. Designers of internal-combustion engines usually make allowance for carbon deposits, which may be expected to collect during a certain period of service. If this deposit increases beyond the critical point, however, trouble always follows. Premature ignition often occurs before the decrease in compression volume has reached the danger line.

When the carbon deposit consists chiefly of carbon, the coating may crack and curl up, as mud does when drying. The low heat conductivity of carbon causes the edges or points thus formed to become incandescent from the heat of the explosion. These glowing points ignite the explosive charge before the piston has reached top center, thus giving rise to a very heavy blow on the bearings and the delivery of power in the reverse direction. As a precaution against undue accumulation of carbon deposit, the volume of the compression space of all cylinders should be measured occasionally. This volume should not be allowed to show a decrease of more than about 15 per cent before cleaning. If the method of volumetric measurement is not used, the carbon deposit may be judged by an examination of its thickness on the bottom of the valve caps and on the top of the piston heads.

In the majority of engines a troublesome carbon deposit and heavy exhaust smoke usually attend the use of too light oil. Such an oil is copiously sucked past the piston rings into the combustion chambers. Compression loss results, because of the poor gas seal afforded by light oil. If relief is sought by cutting down the quantity of oil feed, insufficient lubrication of the upper portion of the cylinder walls will result. This is almost certain to cause destructive scoring.

The rapidity with which carbonization proceeds is very materially effected by the adjustment of the carburetor and by the quality of the fuel used. Too rich a mixture (oxygen poor) will tend greatly to increase the residue left on the walls of the explosion chamber, whereas a lean fuel mixture containing more

free oxygen than is required for burning the fuel itself will contribute to the oxidation of the oil residue.

When heavy carbon deposits collect during service, special attention should be given to the quality of gasoline used in the engine. Poorly refined gasolines from many sources contain large quantities of gum-forming and resin-forming compounds, which are deposited on the combustion-chamber walls in the form of heavy carbon deposits. The source of such a carbon deposit resulting from a poor quality of fuel is usually erroneously ascribed to the lubricating oil.

Carbon deposits may be readily removed mechanically or by the oxygen or oxyacetylene process. The burning method of doing this is as follows: The engine is turned on the compression stroke until the piston arrives at top center. One or both valve caps are then removed and a lighted paraffin wick or other means of igniting the gas is introduced into the explosion chamber. The jet of oxygen is then turned onto the flaming wick, and combustion is at once accelerated. This starting heat raises the temperature of the carbon deposit to the point where it burns readily, and, once started, no further aid is needed for combustion other than the supply of oxygen. When combustion is completed, the flame will automatically extinguish itself. In removing carbon deposits by the oxyacetylene process care should be taken not to overheat the piston head or cylinder walls by the application of intense flame; with oxygen this danger is not so pronounced. The spark plugs should always be removed as a protection to the porcelain. When burning is completed, it is imperative to blow out the cylinders with a high-pressure air jet, in order to remove sand, or salt, and other inactive matter. If this is not done, the abrasive dust remaining will seriously score the cylinder surfaces, pistons, and rings.

Lubricating Systems

As far as principles go, lubricating systems, without exception, may be divided into two general groups: (1) "all loss" systems, (2) "circulating" systems. By "all loss" system is

meant a lubricating system in which the oil is fed directly into the crankcase or through the bearings into the crankcase from an outside source. In this system the lubrication of the parts in contact is accomplished by (*a*) splash alone from the connecting-rod ends and by (*b*) oil under pressure as well as by splash from the connecting-rod ends. In engines employing "all loss" systems, oil is filled up to a fixed level in the crankcase. The lubrication of all parts is then made continuous by splash and by feeding oil from an auxiliary source into the crankcase, where it is consumed at about the same rate as the feed. "All loss" systems are, however, much less fool-proof in many ways than are the circulating systems. With the former there is a possibility of feeding an excess of oil into the crankcase, which may cause a rapid carbon deposit in the cylinders; or, on the other hand, of feeding too little oil, thereby causing unduly rapid wear or perhaps serious injury to the parts from lack of lubrication.

By "circulating" system is meant a lubricating system in which a quantity of oil is filled to a fixed level into the crankcase sump, whence it is continuously *circulated* by some type of pump to all parts requiring lubrication. In all circulating systems the oil is applied to the moving part by (1) splash alone from connecting-rod ends or (2) pressure and splash from the connecting-rod ends.

The various systems in use under the above-mentioned principles may be roughly grouped as follows: (1) splash lubrication, (2) semisplash lubrication, (3) forced lubrication, and (4) oil fed with fuel.

Splash Lubrication

In this system a quantity of oil is poured directly into the crankcase through a strainer and is maintained at an approximately constant level by occasional supplies from an outside source. As the engine turns, the lower ends of the connecting rods, or dippers on the connecting rods, strike the oil and splash it in all directions, thus filling oil cups which feed the main

bearings. The lower ends of the connecting rods, or the dippers on them, catch part of the oil and feed it to the crankpin bearings through holes bored in the connecting rods. Part of the oil is splashed onto the walls of the cylinder and lubricates the cylinder, piston, and piston rings. Another part is splashed into the hollow pistons, where it collects under the piston heads and drops through slots cut in the upper ends of the connecting rods and lubricates the wristpins. The camshaft parts catch the oil in pockets and feed it, by means of holes bored through them, to the bearings. The distribution gears and push rods are lubricated by the oil which splashes over them.

This system is used on some automobile engines and to a greater extent on low-speed marine engines.

Semisplash Lubrication

This system is similar to the above except that a circulating pump is used to suck the oil from the sump formed in the bottom of the crankcase, and deliver it to a channel or trough extending the full length of the crankcase. From this trough the oil overflows into separate compartments under the connecting rods, maintaining a constant level in each, the surplus oil returning to the sump. The dippers on the connecting rods strike the oil as the engine turns, and splash it in all directions, as described under the splash system.

After passing through the various bearings the oil is usually returned to the sump, where it enters the circulating pump and the process is repeated.

In one variation of this system part of the oil may be pumped into pockets, from which it is fed by gravity to the main bearings, gears, etc., the other bearings being lubricated by the splash.

In another variation of the semisplash system the oil is forced, under pressure, through pipes to the main bearings. From the main bearings it may be forced through ducts bored in the crankshaft to the crankpin bearings. The remaining surfaces are then lubricated by the splash system, as above described.

The semisplash system of lubrication is the one used on the majority of automobile, tractor, and 4-cycle marine engines. This system or one of its variations is suitable for all 4-cycle engines except those operating at very high speeds, where full-force feed lubrication is necessary.

Forced Lubrication

With very high speeds the pressure on the bearings, particularly during the latter portions of the working stroke becomes very great, owing to the inertia of the reciprocating parts. In order to resist this pressure, either larger bearing areas or forced lubrication of the bearing must be provided. Furthermore, at very high speed the reversals of pressure at the crankpin would cause knocking and vibration unless the bearings were fitted very closely, and hence forced lubrication again becomes necessary. This is the condition that we find in all aircraft engines, high-speed marine engines, and racing automobile engines.

In this system of lubrication the oil is poured into the crankcase of the engine through a suitable strainer, as in the other systems. It is drawn from the reservoir in the sump of the engine by a circulating pump, usually of the rotary-gear type, and forced, under a pressure of from 20 to 50 pounds per square inch, through oil pipes or ducts to the camshaft bearings and to the main bearings. From the main bearings the oil is forced, under pressure, through holes bored in the crankshaft to the crankpin bearings. From the latter bearings it is again fed, through oil pipes attached to the connecting rod, to the wristpins. Oil escaping from the wristpins and crankpins lubricates the cylinders, pistons, and piston rings. The push rods are lubricated by the splash of oil from other parts.

Some engines employing this system of forced lubrication have provision for additional oil feed, under pressure, to each cylinder, the feeds being controlled by the speed of the engine.

After having passed through the various bearings the oil is returned to the sump through a strainer, where it enters the

circulating pump and circulates again as described. For the guidance of the operator an oil pipe usually connects the oil-pressure line with a pressure gauge mounted on the gauge board.

Aircraft Engine Lubrication

There are two ways of carrying the lubricating-oil supply for aircraft engines: (1) the wet-base and (2) the dry-base systems. In wet-base engines the entire supply is carried in the sump.

In dry-base engines the whole oil supply is carried in a secondary tank separate from the engine but directly connected to it through inlet and outlet pipes. The advantages possessed by the dry-base system over the wet-base system consist in the better cooling of the oil, the separation of sediment from the oil in circulation, and the adequate lubrication of cylinders and pistons during flight. The extraordinary evolutions described by airplanes in fighting make it a matter of vital necessity to operate engines inclined at all angles,— to the vertical as well as in the upside-down position. To meet this situation lubricating systems have been elaborated so as to deliver to all parts an abundance of oil for their lubrication and to carry off excessive friction heat. Forced-feed lubrication is applied to all aircraft engines and distributes oil under considerable pressure to all friction points.

In dry-base engines the oil issuing from the bearings drains down to the suction side of a second pump located in the bottom of the base chamber, which tapers from the end towards the center. This evacuating pump, being of greater capacity than the pressure pump which forces oil to the bearings, prevents the accumulation of oil in the crankcase and forces it to a separate oil reservoir-cooler. From the secondary reservoir the oil flows back in rapid circulation to the pump which feeds the bearings. With this arrangement positive lubrication is entirely independent of engine position. The capacity of forced-feed pumps in aircraft engines varies between 1.5 and 2 gallons per minute. In long spiral glides at a steep angle, or in long vertical nose dives from a distance in altitude of from one to two miles, with the engine pulling at full throttle, there will be an accumulation of several

gallons of oil in the crankcase of even the dry-base engine, but usually this quantity will not exceed one third of that carried in the sump of a wet-base engine. The likelihood of flooding the cylinder and of failure of ignition is thereby proportionately decreased in dry-base engines. At present, dry-base engines appear more adaptable than those of the wet-base to the long-continued trick flying required by actual battles in the air. The forced-feed lubricating system in wet-base engines differs in no special way from the same system applied to automobile engines.

The construction and operation of rotative radial-cylinder engines introduce additional difficulties of lubrication and merit especial attention. Owing to the peculiar alimentation system of the rotary-type motors, atomized gasoline mixed with air is drawn through the hollow stationary crankshaft directly into the crankcase, which it fills on the way to the cylinders. This crankcase is also partially filled with oil and therein lies the trouble. Hydrocarbon oils are soon dissolved by the gasoline and wash off, leaving the bearing surfaces without sufficient protection and exposed to instant wear and destruction. So castor oil is resorted to as an indispensable but in some ways an unfortunate compromise. Being of vegetable origin, castor oil is highly susceptible to direct oxidation, and for this reason it leaves a much more bulky carbon deposit (oxidation products) in the combustion chamber than does mineral oil, and also causes the formation of a gummy deposit in the crankcase.

All engines employing castor oil, whether water-cooled or air-cooled, must be dismounted and thoroughly scraped out at frequent intervals. When used in air-cooled engines, or in water-cooled engines where the pistons become overheated, the use of castor oil has the great advantage of preventing the occurrence of dry spots caused by severe local overheating. For the lubrication of rotative aircraft engines it is advisable to use only unblended, chemically pure castor oil, first because of its relative insolubility in gasoline, and, second, for the reason that its high viscosity assures proper lubrication at the high operating temperature which obtains in air-cooled cylinders.

Marine Engine Lubrication

The general conditions under which marine engines work, as regards temperatures, differ materially from those in other types of internal-combustion engines.

Marine engines are cooled by the vigorous circulation of comparatively cold water through the jackets of the cylinders. The water is picked up fresh, forced through the cylinder jackets, and discharged back into its source. Hence the operating temperature of a marine engine is relatively lower than the temperature at which automobile or aircraft engines operate.

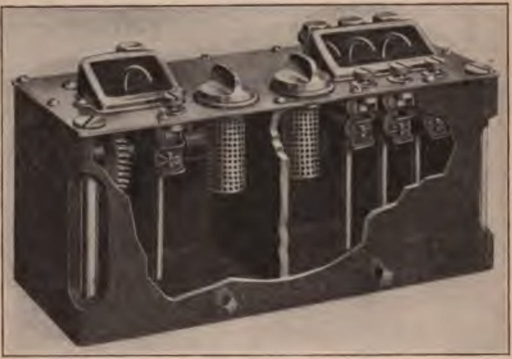


Fig. 55. Mechanical lubricator

This condition of affairs determines the character of the oil which should be used for the lubrication of motor-boat engines. As a rule a much lighter oil may be used, because of the lower temperature of the engine parts. The light or medium grade of oil also deposits less carbon at this low temperature than does a heavier oil.

Oil engines and 2-cycle gasoline engines cannot be lubricated by the splash system, as the air or mixture in the base would carry a portion of it into the cylinders, with the liability to preignition in the oil engine and of other troubles in the gasoline engine. One of the several forms of forced feed is therefore adopted, the mechanical oiler having the preference. The mechanical lubricator consists of a rectangular reservoir containing a series of small pumps, all operated from a single shaft, which is in turn driven by some rotating or oscillating part of the engine. Pipes lead from each pump to the desired

point. The amount of oil pumped per stroke is regulated in each pipe, and sights are provided to observe the feed. The rate of feed is regulated by experiment until it is about equal to the rate of consumption, as none of the oil is recovered. In Fig. 55 is shown a mechanical lubricator which is used on many 2-cycle gasoline engines.

Oil fed with Fuel

This system is employed successfully for lubricating very small 2-cycle marine engines. It consists of mixing approximately one pint of oil with each five gallons of fuel. The oil passes through the carburetor with the gasoline and is deposited on the cylinder walls. The oil vapor in the crankcase lubricates the crankpin and wristpin bearings. The main bearings are usually lubricated by grease cups. In rare instances oil is fed from a drip cup into the inlet manifold and carried to the cylinders by the fresh explosive charge.

CHAPTER X

COOLING THE ENGINE

On account of the intense heat generated by the combustion of the fuel in an internal-combustion engine, some means must be provided to keep the temperature within proper bounds. It is apparent that the rapid combustion would soon raise the metal portions of the engine to a red heat if some means were not provided to conduct much of the extra heat away. The high temperatures of the parts would burn the lubricating oil, and the piston and rings would expand to such a degree that they would seize in the cylinder walls, and the engine would soon become inoperative.

The two general systems of engine cooling in common use are water cooling and air cooling.

Water Cooling

When water is used for cooling, the cylinder is made with a double wall, the space between the two walls being called the water jacket.

The water jacket should cover the entire length of the stroke, to avoid unequal expansion in the cylinder bore and burning of the lubricating oil. The water space should be wide and, in large cylinders, cleaning holes should be provided. The life of the cylinder can be materially increased if cleaning is done at regular intervals of from four to eight weeks, according to the purity of the water used.

The water which is used for cooling is circulated through the water jackets which surround the cylinder barrel. The water may be kept in motion by two methods. The method generally employed is to use a positive circulating pump, usually a

centrifugal pump, which is driven by the engine to keep the water in motion. The second method is to utilize the principle that heated water is lighter than cold water, the heated water rising to the top of the cylinder and the cooler water taking its place at the bottom of the water jacket. The latter method is called the thermo-syphon system of cooling. The thermo-syphon system is particularly applicable to engines having their cylinders *en bloc*, and in such cases adds to the simplicity of design. With separately cast cylinders it is awkward to provide the large water connections necessary.

A typical water-cooling system of a 12-cylinder automobile in which a pump is depended upon to promote circulation of the cooling water is shown in Fig. 56. The radiator is carried at the front end of the car and serves as a combined water tank and cooler. It is composed of an upper and a lower portion joined together by a series of pipes, which may be round and provided with a series of fins to radiate the heat, or which may be flat in order to have the water pass through in thin streams to cool it more easily. In Fig. 56 the radiator is of the flat or ribbon-tube type, and the radiator core through which the water passes is independent of the outer shell, and so is easily removable in case any repairs should become necessary.

The water is drawn from the lower header of the radiator by the centrifugal pump and is forced through a manifold to the lower portion of the water jackets of the cylinder. After leaving the cylinder jackets the warm water passes through the cored jacket surrounding the intake manifold, and thus assists in the vaporization of the gasoline. The water then passes to the upper portion of the radiator. Here it is divided in thin streams and directed against the comparatively cool metal which abstracts the heat from the water. As it becomes cooler it falls to the bottom of the radiator and is again circulated around the cylinders of the motor as before. A cooling fan, which draws currents of air through the interstices of the radiator, is used to assist in cooling the water.

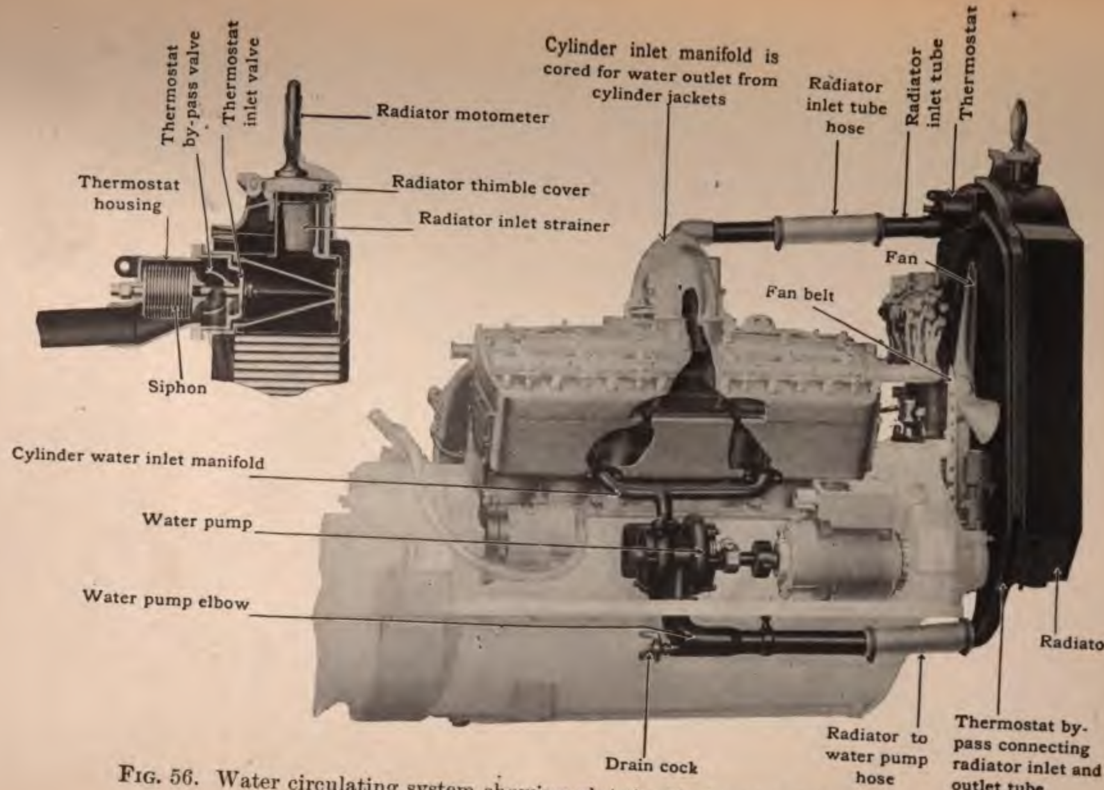


FIG. 56. Water circulating system showing alsó the block construction of cylinders

Cooling System of a Modern Aircraft Engine

Water jackets around the cylinders can be formed in various ways. In nearly all automobile engines and marine engines the jackets are cast integral with the cylinders. Sometimes the jacket is made of sheet metal, brazed or welded to the cylinder. This type of jacket is used when the cylinders are made of steel, as in the Liberty engine. A cylinder for this engine is shown in Fig. 57 and in Fig. 58 is shown one type of radiator used on aircraft engines.

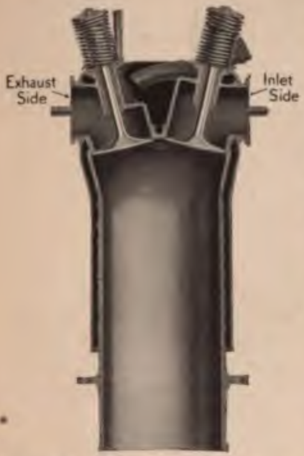


Fig. 57. Cylinder for Liberty engine, half in section, showing jacket, valves, and holding-down flange

Cooling water is circulated through the Liberty engine by means of a centrifugal pump, shown in section in Fig. 59. The pump runs at one and one-half times engine speed. The capacity of this pump is 100 gallons per minute at 1700 revolutions per minute. The cooling system from the pump inlet, to and including the water outlet header, will hold 5.5 gallons of water.

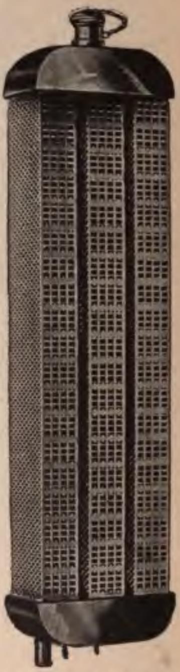


Fig. 58. Radiator for an aircraft engine

The water pump is provided with a single inlet, the outside diameter of which is two inches, and two outlets, each one delivering water to one of the headers which supply the right-hand and left-hand cylinders. Water is forced into each cylinder jacket tangent to its outside surface. This construction gives the water a whirling motion inside the jacket and insures uniform cooling.

The water-outlet pipe for each cylinder extends inside the jacket to a point very close to the exhaust-valve chamber, shown in Fig. 57. This guarantees the proper cooling of the exhaust valve. The cooling water then goes through a passage cored in the intake headers. This serves further to vaporize the incoming gas as well as to assist in cooling the water. These passages in the

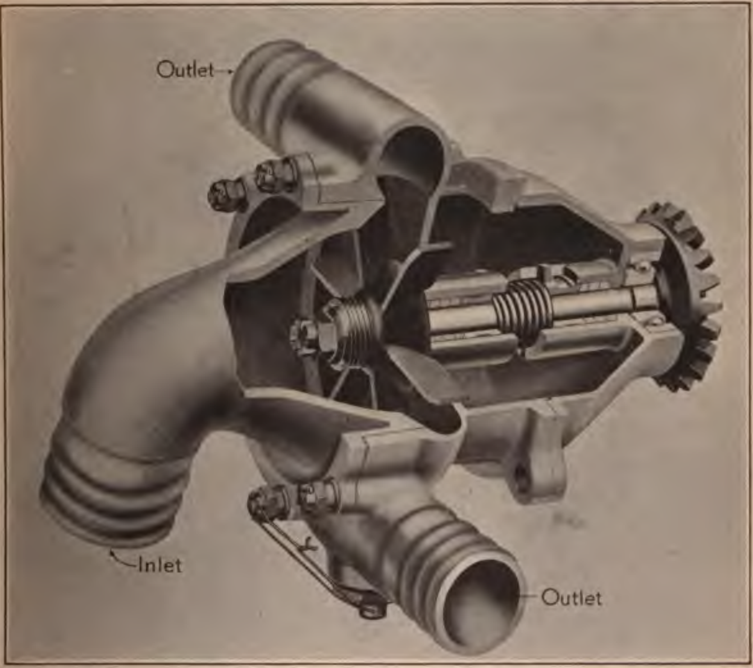


FIG. 59. Centrifugal water pump for Liberty engine

intake headers are connected by two water-outlet headers, the final outlet of which has an outside diameter of two inches. The motion of the plane in flying circulates air through the radiator (Fig. 58) and cools the hot water from the water jackets.

The thermo-syphon system is not common on aircraft engines on account of the increased weight of water required with that system and the close regulation of temperatures demanded for aircraft engines.

Cooling of Marine Engines

Marine engines are almost invariably cooled by the positive circulation of water. The arrangement of circulating-water piping for a navy-type engine is shown in Fig. 60. A circulating pump of the plunger type takes its suction from the sea through

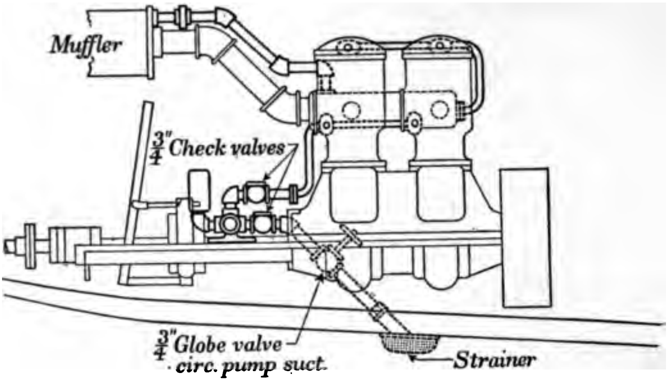


Fig. 60. Arrangement of circulating-water piping on a 2-cylinder, 2-cycle marine engine

a combined scoop and strainer, and discharges the water to the cylinder jackets at their lowest points. After circulating through the jackets the water leaves at the cylinder heads and enters the water jacket of the exhaust manifold at the forward end. From the after end of the manifold, the water is piped to the muffler and thence overboard.

Temperature of Circulating Water

All water-cooled aircraft engines, many automobile engines, and some marine engines are fitted with a thermometer of some kind for indicating the temperature of the circulating water leaving the jackets. On aircraft engines the instrument dial is carried in the cockpit; on automobiles it is located in the upper tank of the radiator. The thermometer is the pulse of the cooling system and is most important, as it will indicate at once any

overheating of the motor. If proper attention is paid to the thermometer readings, the cause of the overheating may be remedied before it becomes dangerous. The proper reading should be between 165° F. and 175° F.

Overheating is generally due to one or more of the following causes: (1) Running with too rich a mixture; (2) insufficient spark advance; (3) carbonized cylinders; (4) fan belt slipping (automobiles); (5) radiator not filled; (6) circulating system clogged with scale, rust, or dirt; (7) insufficient lubrication; (8) pistons fitted too tightly.

Air Cooling

The simplest system of air cooling is that in which the cylinders are provided with a series of flanges which increase the effective radiating surfaces of the cylinder. These cooling flanges, or metal fins, absorb the heat of the explosions and diffuse it in the rush of the air. This increase in the available radiating surface of an air-cooled cylinder is necessary because the air does not absorb heat as readily as water, and therefore more surface must be provided to dissipate the heat and to prevent injury to the cylinders. In air-cooled aircraft engines the cylinders are placed directly in the path of the propeller slip stream, and often a fan is used to increase the rate and degree of cooling.

Fig. 61 shows an air-cooled cylinder, half in section. It will be noticed that the fins are longer around the top of the cylinder where the most intense heating, due to the explosion, takes place. The principal advantage of air cooling is the reduction of weight through the elimination of the various parts of the water-cooling system. Rotary radial-cylinder types have proved practical with air cooling, but it is generally conceded that the water-cooled motor is best for long flights. Two-cycle motors cannot be sufficiently cooled by air.

In Fig. 62 is shown an automobile power plant which is cooled successfully by an ingenious system of air circulation. Each cylinder is provided with fifty-two vertical steel flanges, or

ribs, which project from the outside walls and extend almost the entire length of the cylinder. Cylindrical aluminum sleeves, surrounding the flanges on each cylinder, form a connection with a sheet-metal deck which horizontally divides a compartment, inclosed by the hood on top and the diaphragm on the bottom, into two compartments that are approximately air-tight.

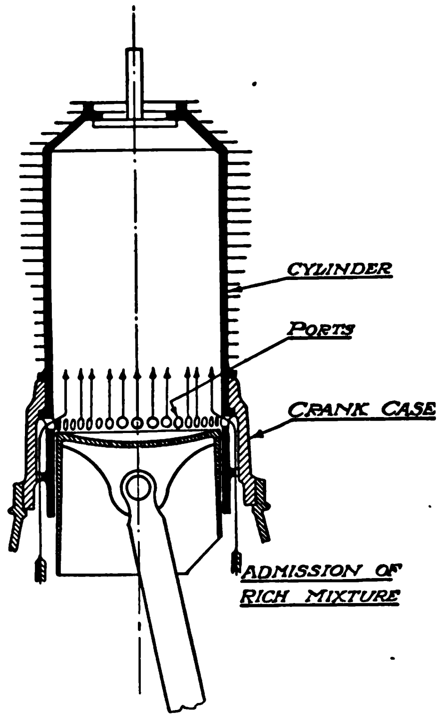


FIG. 61. Air-cooled cylinder for an aircraft engine of the rotary type

The rotation of the flywheel, which incorporates a centrifugal fan having a capacity of 2200 cubic feet per minute, sets up a suction which causes air to rush into the grilled opening in front of the hood, down through the flanges, and out through the flywheel.

There is no cooling action when the hood is raised. The engine should never be run in this condition for more than a few minutes at a time.

Air-cooled motors are limited to small sizes. They use less fuel than the water-cooled engines because the higher temperature of the cylinder does not permit a full charge of gas to be admitted on the intake stroke. Air-cooled engines cannot, as a rule, be operated for extended periods under overloads or at

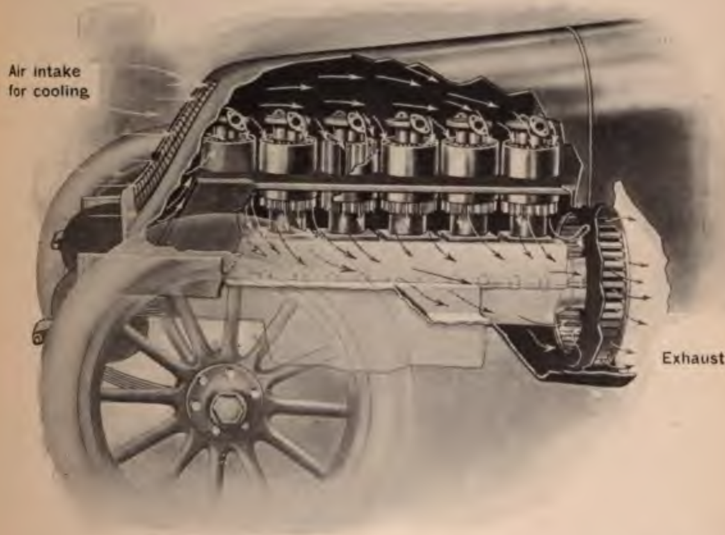


FIG. 62. Air-cooling system of a well-known automobile engine

very high speed without heating to such a point as to cause premature ignition. When properly used, air-cooled engines give good results and are economical. Nearly all automobiles, however, are provided with water-cooled power plants. Motorcycle engines, on the other hand, are with few exceptions cooled by air.

THE UTILIZATION OF THE HEAT FROM THE WATER JACKETS

It is possible to utilize some of the heat which the water jackets carry away, but the extra complications and the increased cost of installation are hardly repaid by the saving effected. With large engines the limit, theoretically, will be about 12 per

cent of the jacket and exhaust heat, recovered as work. With smaller engines the saving is, of course, considerably less.

An engine utilizing the heat from the water jacket and the exhaust has recently been developed in England by Mr. W. J. Still. The Still engine makes use of the recoverable heat which passes through the surfaces of the combustion cylinders, as well as in the exhaust gases, for the evaporation of steam, and this steam is expanded in the combustion cylinder itself on one side of the main piston, the combustion stroke acting on the other side. It increases the power of the engine and reduces the consumption of fuel per horse power.

CHAPTER XI

THE REGULATION OF SPEED AND POWER; EFFICIENCIES, ETC.

The methods adopted for regulating the speed or power of internal-combustion engines may be classified as follows:

1. Qualitative regulation (variation of the proportion of fuel to air with change of load).
2. Quantitative regulation (throttling of the quantity of fuel and air without changing the proportions).
3. Hit-and-miss system (omitting the working charge entirely so that no working stroke occurs until the speed falls to normal).
4. Variation of the time of ignition.
5. Combination of throttling and variation of the ignition point.

Qualitative Regulation

Variation of the ratio of fuel to air may be accomplished by varying the duration of opening of the gas or oil valve during the inlet stroke, the air admission remaining constant; by delaying the closing of the exhaust valve so that some exhaust returns to the cylinder, thus diluting the working mixture; or by throttling the gas supply throughout the suction stroke but not changing the air admission.

In this system of regulation, as the total quantity of the working charge remains fairly constant, the compression is nearly the same at all loads, and hence the efficiency, as far as compression is concerned, is not greatly reduced. The difficulty with this system is that the inflammability of the mixture is so widely varied by the proportion of gas to air that with a given compression the mixture may fail to ignite at the beginning of the working stroke, and a charge of combustible

mixture will be expelled through the exhaust, with a waste of fuel, the loss of a working stroke, and the danger of back-fires.

At low loads this system is inferior to the quantitative system; the fuel consumption per horse power increases very rapidly as the load decreases, because as the fuel ratio is decreased the mixture rapidly becomes difficult to ignite and slow in burning. The qualitative method of regulation is unsatisfactory at light loads on account of misfires. Liquid-fuel engines, including the Diesel type, are regulated qualitatively as more or less fuel is forced into the engine. These engines maintain a high efficiency at all loads, since the amount of fuel is not controlled by the necessity of forming an explosive mixture.

Quantitative Regulation

A much more satisfactory system than the preceding one is the throttling of the normal charge, the proportion of gasoline to air in the entering charge remaining constant. This variation of the mass of the working charge may be effected by throttling the charge throughout the whole of the suction stroke or by varying the instant of closing the inlet valve. The latter method of cut-off regulation is the only purely quantitative system, but it is not much used on account of the complexity of valve gear required. With the older forms of carburetors, throttling the charge throughout the whole of the suction stroke was never purely of the quantitative type, since the mixture proportions became upset by the increased suction on the air. In such a case the mixture became richer as the load was diminished. With the more modern forms of carburetors, already described (see Chapter VI), this condition has been overcome so that the proportions of fuel to air are maintained constant under all conditions of load and speed.

In quantitative regulation the reduction in the mass of the charge at light loads causes a decrease in the compression pressure, and hence a lowering of the thermal efficiency at such times. This system has the advantage of having an ignition and a working stroke in every cycle. By keeping the mixture

in constant proportions the danger of failure in the ignition is greatly lessened. The pressure in the cylinder is less by reason both of the diminished amount of fuel and of the diminished compression.

The mechanical details of this system of regulation are simpler than those necessitated by qualitative regulation, and at light loads the frictional resistances in the engine are diminished with the decreased compression. The advantages of this system are such that the tendency is to make use of it more and more, either exclusively or in connection with the variation of the point of ignition.

Hit-and-miss System of Regulation

This system was for a long time almost universally used with stationary engines and is still being manufactured, especially in the smaller engine sizes. Its most important advantage is that of giving economical fuel consumption at light as well as at full loads, since the number of working strokes is proportioned to the load. The quality and quantity of each working charge admitted to the engine is always the same. It is simple mechanically, not likely to get out of order, and is inexpensive to manufacture.

The main objection to this system, when close regulation is required, is that the missing of a working stroke results in an inoperative complete cycle. On a 4-cycle single-cylinder engine, one missed explosion means that the engine must make 8 strokes, or 4 revolutions, without a power stroke, which shows conclusively that close regulation cannot be expected. This fluctuation of speed can only be brought within practicable limits by using very heavy flywheels. If the load suddenly increases just after the charge has been missed, there will be a notable reduction in speed, and even with a large weight of flywheel the variation in speed can be detected. For small engines used to drive machinery which does not require close regulation, the hit-and-miss system is to be preferred on account of its high efficiency and low fuel consumption.

There are several methods by which an engine can be made to miss the working stroke. The simplest method is to break the ignition circuit for the required number of strokes. This is most wasteful, for the fuel would be drawn into the cylinder and discharged into the exhaust unburned, and thereby the most important advantage of the hit-and-miss system would be lost.

Another method is to keep the fuel valve closed, so that air only enters during the suction stroke, thus cooling the cylinder walls. In this method the fuel economy is maintained, but the next entering mass of charge will exceed the normal on account of the lower temperature of the cylinder, due to the scavenging action of the fresh air. The resulting explosion pressure is accordingly greater than that attained under normal working conditions.

A third method is to keep the exhaust valve open during the suction stroke. In this method no vacuum is produced, and no charge enters the cylinder. The cylinder walls in this case are not cooled to the same extent as before.

The fourth method, the one generally used, is to allow the inlet valve to remain closed during the suction stroke, thus causing the creation of a partial vacuum within the cylinder during this stroke. In many engines two inlet valves are provided, one for air only, and one for the gaseous mixture. By means of suitable cams the gas valve is kept closed, allowing the air valve to open and permitting a small quantity of air to enter into the cylinder during the suction stroke. This produces a scavenging action, but the cylinder is not cooled as much as in the second method above described.

Regulation by Varying the Time of Ignition

Nearly all modern gasoline engines use electrical methods of ignition. The ignition is so arranged as to be capable of advancement or retardation by hand, sometimes independently and sometimes in connection with the throttle movement.

When the ignition is retarded, the spark does not occur when the return of the piston on its compression stroke has

produced the greatest pressure of the mixture in the compression space, but takes place after the piston has begun to move forward on the expansion stroke. It is obvious that the ignition of the mixture at this time will not develop the same amount of available power as if ignition took place at the point of maximum compression. If the spark is still further delayed, the impulse from the explosion is still more reduced.

One difficulty with this system of regulation is that the length of the stroke may not be sufficient for the complete combustion of the mixture before the exhaust valve opens; and the combustion will continue into the exhaust passages, causing objectionable heating of the cylinder, objectionable noise due to the pressure in the escaping gases, and possible exhaust explosions. It will be seen that a considerable amount of power and fuel are wasted in this method of regulation.

Regulation by Combination of Throttling and Variation of Ignition Point

This method of regulation depends upon advancing the time of ignition to the most efficient point after the engine has once been started and varying the amount of mixture supplied to the cylinders. The spark and throttle levers are usually moved with a certain definite relation to each other. The method is used on automobile, aircraft, and motorboat engines, where it is desired to vary the speed of the engine as well as its power. It is employed on account of its extreme convenience and adaptability, in spite of its inherent wastefulness.

The greatest economy of fuel will result when the engine is driven with as little throttle opening as possible and with the greatest spark advance the motor speed will allow. To obtain maximum power, as in climbing on the direct drive, the spark lever should never be advanced more than half its range, and the throttle should be opened as wide as possible. For extremely high speeds the throttle should be advanced to a point about midway of its travel before the spark lever is advanced beyond that point. If this does not give the required increase

in speed, the spark lever should be advanced as far as possible and the amount of charge increased by moving the throttle lever from its central position to the extreme position on the sector.

The amount of spark advance needed depends on engine speed, and the greater the piston velocity the more the spark should be advanced. It is possible to advance the spark too far, and when this occurs the explosion takes place before the piston reaches the top of its stroke. The injurious back pressure on the piston reduces the capacity of the motor, and a pounding noise gives positive indication of premature ignition due to excessive spark advance. To correct this, retard the spark until this distinct pounding noise disappears.

Attempts have been made to put the time of ignition under automatic control. Automatic regulation of the time of ignition is very difficult to carry out properly, owing to accidents of operation. On the contrary, hand regulation of the spark serves its purpose very well and is consequently coming into more and more extended use for modern internal-combustion engines.

EFFICIENCIES

Effect of compression on efficiency. The thermal efficiency of an internal-combustion engine increases with an increase in its compression pressure. This can be shown from both theoretical and practical considerations. The theoretical aspect has been shown in a preceding chapter. From the practical point of view the effect of increased compression ratio is to affect thermal efficiency in several ways, which will be considered here.

The losses of heat from the burning fuel in the cylinder depend principally upon (1) the total internal area of the exposed walls; (2) the time available for the heat loss to take place; and (3) the density of the charge of mixture.

In an engine the total internal area exposed at the end of the compression stroke will be relatively smaller as the compression ratio is increased, and the effect of the smaller area exposure is to reduce the heat loss. As engines with high

compression usually run at high speeds, the time available for the heat loss to take place is lessened.

The influence of the density of the charge upon heat loss may be summed up by saying that as the compression ratio is increased the density of the charge goes up and the temperature of the compression is raised. For an increase of the ratio of compression from 4 to 6 the rise in temperature will amount to about 200° F.

The net effect, then, of the above-mentioned three factors is to reduce the heat loss from the charge to the cylinder walls as the compression pressure increases.

With high compression there is a smaller volume of exhaust gases left in the cylinder to dilute the incoming fresh charge. This decrease in exhaust-gas dilution increases the efficiency, as a relatively larger volume of the charge is available for the explosion. Experiments show also that the explosion period is shorter and the mean effective pressure greater when high compression is used.

Measurements of the fuel consumption and of the indicated horse power at various compressions show that, beginning with a compression ratio of 4.0 and gradually increasing this ratio up to 8, the increase in thermal efficiency is nearly constant, increasing from 30 per cent with the lower compression ratio to about 40 per cent with the higher ratio.

The upper limit of compression is fixed by the heat losses to the walls, the temperature of the cylinder walls, the strength of the working parts, and the ignition temperature of the explosive mixture used. The ignition temperature varies with the composition of the fuel and the strength of the mixture. Generally the lower the heat value of the charge the higher is its temperature of ignition.

In modern Otto-cycle engines the compression ratio usually lies between 3.5 and 5 for ordinary touring engines, and between 4.5 and about 6.5 for aircraft and other very high-speed engines. The compression ratio in Diesel engines is several times greater than in Otto engines and ranges from 12 to 14.

The Effect of Speed upon Efficiency

It is generally well known that as the speed of an internal-combustion engine is increased up to a certain limit, the thermal efficiency increases. This is due to the fact, already shown, that when the engine is running at high speed the time of charging, compressing, and exploding the mixture is relatively much shorter, and consequently the heat exchange between the gases and the cylinder walls is less than at a lower speed.

Practical considerations connected with the design of valves and gas passages, weight of moving parts, etc. fix the upper limit of speed, however, so that as a general rule the best thermal efficiency is reached at some point before the maximum speed of the engine is attained.

Volumetric Efficiency

The quantity of charge drawn into the cylinder of an internal-combustion engine is always less than the theoretical quantity of charge which would fill the working volume of the cylinder at atmospheric pressure and temperature, and the ratio of the actual to the theoretical quantity is called the *volumetric efficiency.*

To obtain the best results from any type of internal-combustion engine, every effort must be made to obtain the highest possible volumetric efficiency. The actual volumetric efficiency attainable depends upon (1) the temperature of the working mixture as it enters the cylinder, (2) the resistance to its entry due to restrictions in the valves and piping, and (3) the residual pressure of the exhaust products in the clearance space.

The weight of fresh charge drawn into the cylinder depends upon the rate of flow, the amount of obstruction encountered, and the temperature and shape of the induction system. In practice the inlet velocity of the charge varies from 120 to 250 feet per second, according as the engine is a normal or high-speed type. It is desirable to keep the inlet velocity as low as 130 feet per second, if possible, in order to insure high

volumetric efficiency. This is usually accomplished in high-speed engines by increasing the diameter of the valves and passages.

One of the defects of the ordinary 2-port or 3-port type of 2-cycle engine is the low volumetric efficiency obtained with crankcase compression. This low volumetric efficiency is detrimental to high powers and economical operation. The improvement of this type of engine lies in the attainment of higher volumetric efficiency.

Mechanical Efficiency

The power actually generated in the cylinders of an engine is greater than the power delivered to do useful work. The ratio of these two powers is called the mechanical efficiency and is equal to the useful horse power (called brake horse power) delivered, divided by the indicated horse power of the engine. The difference between the brake and indicated horse power is power absorbed in friction, in opening valves, and in operating oil and water pumps, etc.

It is obvious that the more power required to operate the auxiliaries of an engine, the less will be the mechanical efficiency. In a Diesel engine the power required for the air compressor, which furnishes the high-pressure air for the fuel injection, must be charged to the engine. This decreases the useful work for a given indicated horse power and cuts down the efficiency in proportion. The effect of increased speed is to cause an increase in these losses.

In gasoline engines of good design, the mechanical efficiency may be as high as 90 per cent at low speeds, falling off to about 80 per cent at high speeds. In 2-cycle engines of the 2-port or 3-port type the mechanical efficiency falls from about 83 per cent down to as low as 70 per cent and less at maximum speed. The mechanical efficiency of the Diesel engine is less than that of the ordinary Otto-cycle engine.

CHAPTER XII

THE MEASUREMENT OF POWER, INDICATORS, AND INDICATOR DIAGRAMS

Power is defined as the rate of doing work, which in turn is the product of a force multiplied by the distance through which the force acts. The unit of power employed by engineers is the horse power which is equal to work done at the rate of 33,000 foot pounds per minute.

Instruments for measuring power are in general of two kinds: (1) Those absorbing the power by friction and dissipating it as heat; (2) those transmitting, or passing on, the power they measure, and wasting only a small part in friction. These various devices for measuring power are called dynamometers.

One of the simplest forms of absorption dynamometers is known as the Prony brake, and consists of a lever and blocks supported on a revolving drum, or pulley, which is attached to the source of power. The tendency of the arm of the lever to revolve is prevented by the resistance of a platform scale, or other form of weighing device. The brake horse power is found by the formula $\frac{2\,\pi LnW}{33,000}$, where L is the length of the arm in feet, measured from the center of the pulley to the point of the scale suspension, n is the number of revolutions per minute, and W is the net weight of the power stress in pounds, or the gross weight observed, minus the weight of the arm. The Prony brake may be used to measure powers up to about 100 horse-power at a speed not exceeding approximately 1000 revolutions per minute.

One of the most convenient methods for measuring the power of high-speed engines by means of transmitting the power is to connect an electric generator to the main shaft of the engine. If the efficiency of the generator is known at the particular

speed and output at which it is to be operated, a very accurate method of measuring the power of the engine becomes available. As the amount of electrical power delivered will vary with the speed at which the generator armature revolves, and this in turn is dependent upon the power of the engine under test, it will be evident that the electrical power can be read directly from the recording instruments. For direct-current generators, brake horse power is equal to the product of the volts multiplied by the amperes and divided by the product of 746 times the efficiency of the generator (746 watts is equal to 33,000 foot pounds per minute). An electric generator may be used for measuring powers up to 30,000 horse power and at speeds from 750 to 4000 revolutions per minute.

Low-Speed Indicators

For the purpose of studying the internal changes that occur in the cylinders of internal-combustion engines and for finding the mean effective pressure on the pistons it is necessary to have a reliable and trustworthy form of indicator.

The function of all indicators is to draw, to a suitable scale, a pressure-volume diagram which is exactly representative of the actual changes occurring within the engine, over a working cycle of operations. Aircraft, automobile, and other engines operating at speeds exceeding from 500 to 600 revolutions per minute require special forms of indicators. The ordinary form of steam-engine indicator, designed to work below speeds of 400 revolutions per minute, is totally unsuited to moderate or high-speed internal-combustion engines.

Special forms of steam-engine indicators have, however, been adapted by several manufacturers to the requirements of internal-combustion engines running at these lower speeds. One of these is shown in Fig. 63. This indicator is supplied with three interchangeable pistons having areas of one-twentieth, one-eighth, and one-half square inch, and is fitted with a special pencil arm. The greatest pressure upon the piston should, properly, be between 100 and 125 pounds; and therefore the piston selected

should have an area equivalent to such fraction of the maximum working pressure as will give this result.

The drum ordinarily supplied is one and one-half inches in diameter, this being the preferable size for high speeds, and answering equally well for use at lower operating speeds.

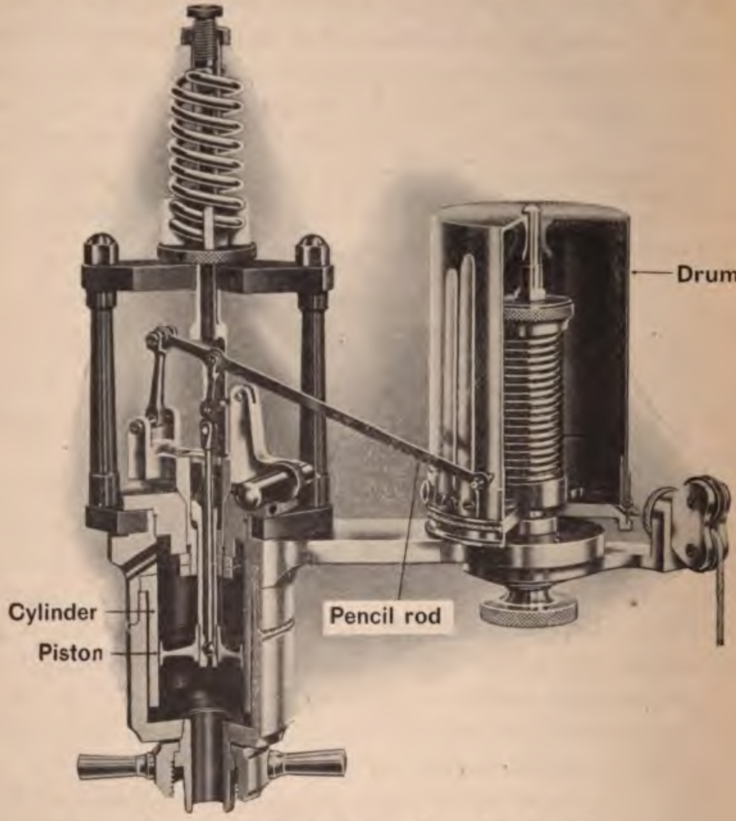


FIG. 63. Indicator for engines of low speed

The principal error of mechanical indicators, when used for high-speed work, is that due to the inertia of the piston and pencil mechanism. In addition to this there are errors due to backlash, friction effects, and the stretching of the cord which gives the drum its motion.

High-Speed Indicators

One of the best high-speed indicators is the manograph, or diaphragm type of indicator, in which the phases occurring in the cylinder deflect a diaphragm which in turn moves a small mirror about an axis in a vertical plane, this movement generating the volume lines, while a somewhat complicated reducing motion deflects the mirror about an axis in the horizontal plane, generating the pressure lines. The combination of the two movements generates the complete diagram. A beam of light reflected from the mirror traces the diagram on a ground-glass or a photographic plate. On account of the lightness and efficient balancing of the mirror, it faithfully responds to every variation of pressure in the engine cylinder even at the highest engine speeds. An instrument of this kind shows practically no inertia effects, and there is no cord used, whereby errors may be caused. The apparatus is particularly valuable for finding the mean effective pressure in the cylinder and in studying the relative merits of various ignition systems, the volumetric efficiency, the action of the carburetor, and the best size and shape for inlet and exhaust valves, etc. The manograph will work in any position and is just as suitable for steam engines as the ordinary indicator. It can be used on any kind of internal-combustion engine having fixed cylinders.

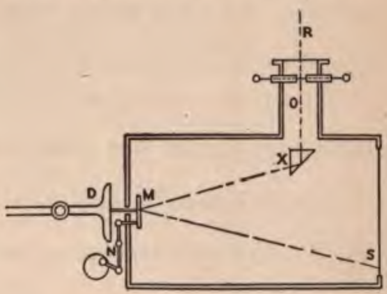


Fig. 64. The manograph

The optical arrangements of one of these high-speed indicators are shown diagrammatically in Fig. 64. The beam of light from the source R enters the light-tight box through a tube O and is reflected by the prism X onto the pivoted mirror M, previously described; from this mirror it is reflected to the ground-glass screen S, which can be replaced by a photographic plate when required. D and N are suitably connected to the engine under test.

Formula for Indicated Horse Power

After obtaining the mean effective pressure in each cylinder the exact formula for the indicated horse power of a single-acting 4-cycle internal-combustion engine having N cylinders, each of d inches bore and l inches stroke, and running at n revolutions per minute, is found as follows:

Denoting the mean effective pressure in pounds per square inch by p, the mean useful indicated force on each piston per cycle is $\frac{\pi}{4} d^2 \times p$ pounds. This acts through l inches, and hence the indicated work per cylinder per cycle is $\frac{\pi}{4} d^2 \times p \times \frac{l}{12}$ foot pounds. As there are n revolutions per minute, there are $\frac{n}{2}$ complete cycles per minute (since there is only one working stroke in two revolutions), and hence the useful indicated work done per cylinder per minute is $\frac{\pi}{4} d^2 \times p \times \frac{l}{12} \times \frac{n}{2}$ foot pounds.

As this is true for each of the N cylinders, the total indicated work for all cylinders is expressed by $\frac{\pi}{4} d^2 \times p \times \frac{l}{12} \times \frac{n}{2} \times N$ foot pounds. It is therefore evident that the indicated horse power of such an engine is $\frac{1}{33000} \times \frac{\pi}{4} d^2 \times p \times \frac{l}{12} \times \frac{n}{2} \times N$.

In the case of a double-acting 4-cycle engine, and also in that of a single-acting 2-cycle engine, there is one working stroke in each revolution, and accordingly the indicated horse power for these is obtained by writing n instead of $\frac{n}{2}$ in the last-mentioned equation.

Indicator Diagrams

The diagram is a record of the pressure in the engine cylinder during the operation of the engine through one cycle. In Fig. 65 is shown an ideal card for an Otto 4-cycle engine. The scale of approximate pressures, in pounds per square inch, at one side, indicates the relative pressure at various points on

the card. The combustion line, which is vertical, indicates that combustion takes place at constant volume as required by the theoretical conception of the Otto cycle.

In the diagrams following Fig. 65 the suction and exhaust curves are omitted for the sake of clearness.

Effect of the Variation in the Time of Ignition

If the ignition is retarded by delaying the spark, the combustion line, which is shown as a vertical line in the ideal card (Fig. 65), becomes inclined to the right, as shown in Fig. 66. The more the spark is delayed the more will the line be inclined to the right. It will also be noticed that the total area of the card is reduced. This fact is taken advantage of in regulating the speed and power of the engine by varying the time of ignition, as previously described.

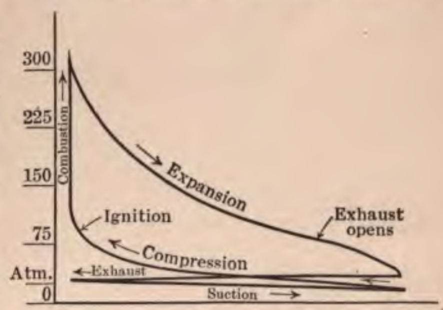


Fig. 65. The ideal indicator card

When the ignition is too early, the combustion line will be inclined to the left, as shown in Fig. 67. The full pressure here is shown to have reached its maximum before the completion of the compression stroke, thus causing a loop at the top of the card. The area of this loop must be subtracted from the area of the card, as it represents negative work. This condition could not exist for any considerable length of time in a single-cylinder, single-acting engine, on

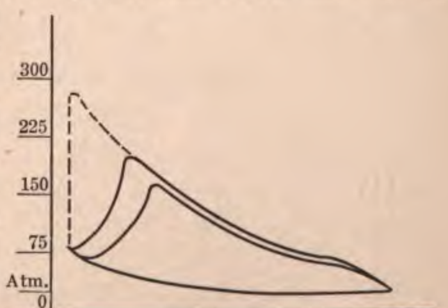


Fig. 66. Effect of retarded ignition

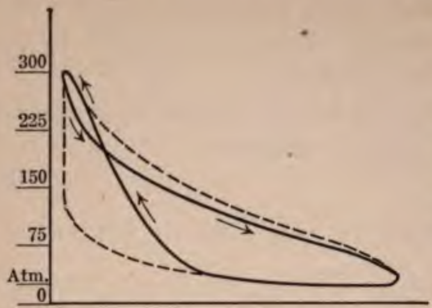


FIG. 67. Effect of too early ignition

account of the small amount of power that the engine would deliver. It may occur continuously, however, in one cylinder of a multicylinder engine (for instance, on account of a defect in timing affecting one cylinder only) and the engine continue to run by the power delivered by the other cylinders.

EFFECT OF LOSS OF COMPRESSION

FIG. 68. Effect of loss of compression

In Fig. 68 is shown the effect of loss of compression on the area and shape of the indicator card. The full card, indicated by broken lines, shows a normal card with full compression. The smaller card shows the loss of work when the compression is lowered, other conditions remaining unchanged.

EFFECT OF A WEAK MIXTURE

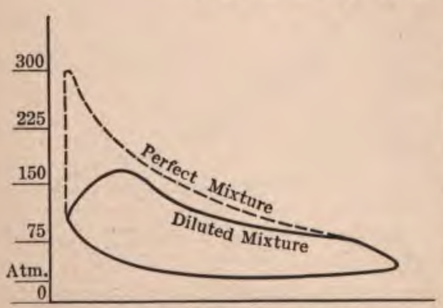


FIG. 69. Effect of a weak mixture

A weak mixture gives the full-line part of the diagram shown in Fig. 69, in comparison with the broken-line part for a perfect mixture in the same figure. The inclination of the combustion line and the lower final pressure for the diluted mixture

are due to the lower rate of flame propagation and the smaller amount of heat energy liberated by the combustion of the impoverished charge.

FIG. 70. Effect of high exhaust back pressure

EFFECT OF THE HIGH EXHAUST BACK-PRESSURE

The effect of small exhaust valves, restricted passages, or improper timing of the exhaust valve is to create in the cylinder a high back-pressure, giving a card like that shown in Fig. 70. The shaded area represents negative work.

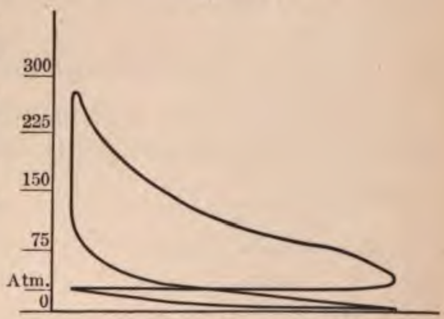


FIG. 71. Effect of faulty admission

EFFECT OF FAULTY ADMISSION

In Fig. 71 is shown the effects of small inlet valves, restricted inlet passages, etc. The vacuum created by the piston on the suction stroke causes a large loop below the atmospheric line. If the flow of the charge were unrestricted, this loop would be very small, as shown in the ideal card, Fig. 65. This condition reduces the volumetric efficiency of the engine and decreases the useful work.

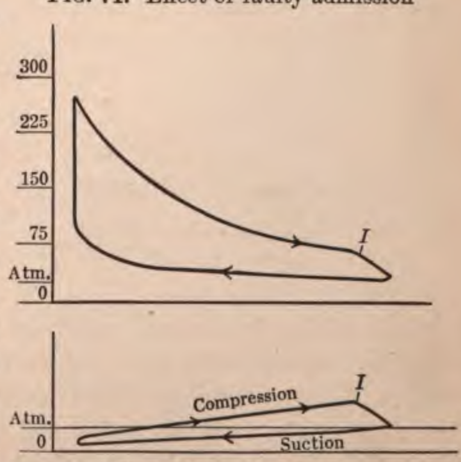


FIG. 72. The cylinder diagram (upper) and crankcase diagram (lower) for a 2-cycle engine

Two-Cycle Engine Diagram

An example of the ordinary diagram and of the crankcase diagram is shown in Fig. 72. The compression of the charge in the crankcase is shown by the rise in the pressure up to point *I* of the lower diagram, where the inlet port opens. From this point the pressure in the crankcase falls below the atmospheric line, indicating that another charge is being drawn in. Point *I* is also shown on the cylinder diagram. It will be noticed that the pressure falls to the atmospheric line here also before the compression stroke begins. This is due to the fact that the exhaust valve is open, permitting the equalization of pressures.

The Diesel Engine Card

In Fig. 73 is shown a normal diagram of a Diesel 4-cycle engine. This diagram is distinctly different from those preceding, as the combustion line here is approximately horizontal, indicating combustion of the fuel at approximately constant pressure during the short period of fuel injection. The suction and exhaust strokes are shown at the bottom of the card and are similar to the corresponding strokes in the Otto-cycle engines.

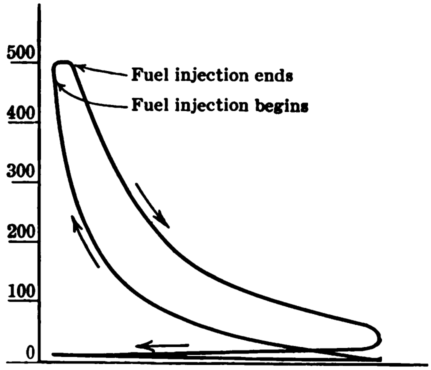


FIG. 73. Diagram for a 4-cycle Diesel engine

The cylinder end of the diagram from a Diesel 2-cycle engine is similar to that shown for the 4-cycle, except that the exhaust and scavenging strokes are not indicated in this figure. The scavenging stroke leaves the cylinder filled with pure air ready for compression and thus takes the place of the suction stroke in the 4-cycle Diesel or Otto engine.

CHAPTER XIII

THE PRINCIPAL ENGINE PARTS AND THEIR FUNCTIONS

Cylinders

One of the very important parts of the internal-combustion engine and one that has an important bearing upon its efficiency is the cylinder unit. The present tendency among automobile manufacturers is to make all cylinders a unit, or block casting, of cast iron, the cylinders and jackets being cast usually in one piece. For aircraft engines, however, the cylinders are usually machined from steel forgings with steel water jackets welded on. A separate cylinder liner or barrel is an advantage, because the separate liner can expand axially, independent of the jacket, which is very important on account of the great difference in temperature between these two parts. To allow for this free expansion the liner is rigidly fastened only at its inner end, while the other end is allowed to move axially. In Fig. 74 is shown one of these aircraft cylinders from a Liberty engine with water jacket in place. Fig. 57, page 126, shows the same cylinder, half in section, with the water jacket welded to it.

Fig. 74. Cylinder of an aircraft engine

The advantage of casting the cylinders in blocks is that a motor may be much shorter and a simpler system of water

piping may be employed than would be the case if individual castings were used. When the cylinders are cast together, as shown in Fig. 75, a more compact, rigid, and stronger power plant is obtained than when cast separately. There is this disadvantage, however, that if one cylinder becomes damaged it will be necessary to replace the entire unit, including the remaining three or more good cylinders. The cooling effect in multiple

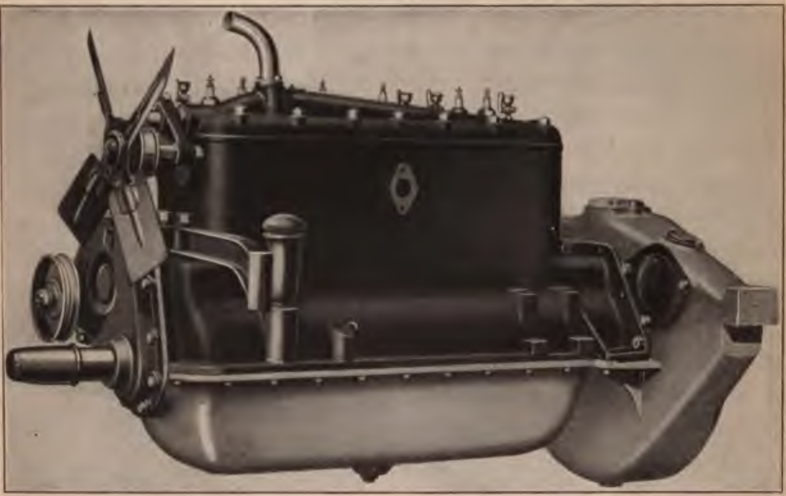


FIG. 75. Showing block casting of a 6-cylinder automobile engine

cylinder castings is not always uniform, and the stresses which obtain because of the unequal expansion may distort the cylinder to some extent. Fig. 75 illustrates a modern 6-cylinder automobile engine having the six cylinders and upper half of the crankcase cast in one block. The cylinder head is cast separately and is easily removed for the purpose of regrinding the valves and removing the carbon.

It is usually impracticable to have more than six cylinders in the vertical type of motor, on account of the great length of the power plant and the much stronger and heavier crankshaft required. When the number of cylinders is increased above six, the solution for the best arrangement is found in two sets of

cylinders inclined at an angle, thus producing a motor of the same length but increased power, called the V-type motor. The angle between cylinders varies from 90° to 45°. The advantages of multiple cylinders are high speed, decreased vibration, flexibility, overlapping power strokes, and lighter reciprocating parts.

Pistons

Although one of the simplest parts of an engine, the piston is one of the most important, inasmuch as it is the member that receives the full force of the explosion and transmits the power obtained from the heat energy of the fuel to mechanical motion by means of a connecting rod to which it is attached, as shown in Fig. 76. It also acts as a crosshead through which the side thrust, due to the angularity of the connecting rod, is transmitted to the cylinder wall. The side thrust of the piston against the cylinder wall causes wear of the piston and cylinder, as well as an increase in the frictional loss. The most obvious way of reducing the thrust would be to decrease the angularity of the connecting rod by making it longer. In practice, however, the allowable length of the rod is limited, since the height and weight of the motor increase rapidly with the length of the connecting rod. Another solution is to offset the cylinder axis from the vertical plane through the crankshaft axis toward the side on which the crank-arm moves during the power stroke. The connecting-rod angle will then be relatively small when the pressure on the piston is high, and proportionately greater when the pressure on the piston is low.

Fig. 76. Piston with connecting rod attached

The piston is usually made of cast iron, steel, or aluminum alloy, machined to fit the cylinder diameter with clearance enough to compensate for the expansion due to the heat and to permit lubrication between it and the cylinder walls. The clearance varies with the material used and with the designed speed of the engine, increasing for the high-speed engines in which greater friction is generated. Since aluminum has a coefficient of expansion almost twice that of cast iron, a greater clearance must be allowed between the piston and cylinder wall to prevent seizing of the pistons when the engine runs continuously under heavy load. The pistons of nearly all later types of aircraft engines are made of aluminum, which, in addition to its light weight, has a high thermal conductivity. The pistons of marine and other engines are usually made of cast iron.

Fig. 77. Piston for a 2-cycle engine

Most pistons are made with a slight taper, being larger on the crank end than on the head end. The reason for this is apparent from the fact that the head end, being subjected to the greatest heat and containing the greatest amount of metal, expands much more rapidly than the crank end.

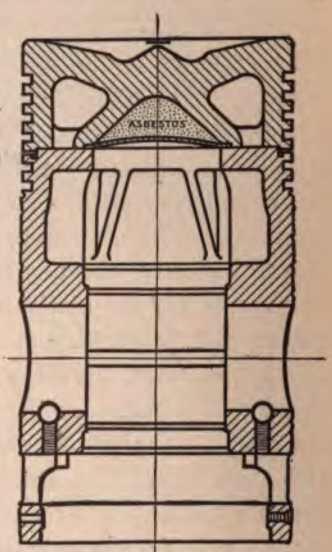


Fig. 78. A piston for a Diesel engine

In Fig. 77 is shown a side view of a cast-iron piston for a 2-cycle marine engine. Note the deflector plate used to prevent the escape of the fresh mixture into the exhaust. In Fig. 78 is shown a section of a conventional Diesel-engine piston taken from an engine developing 80 horse power per cylinder. Fig. 79 shows a conventional

Otto-cycle-engine piston in which the weight has been reduced to the extreme limit. The ribs used to stiffen the piston and to

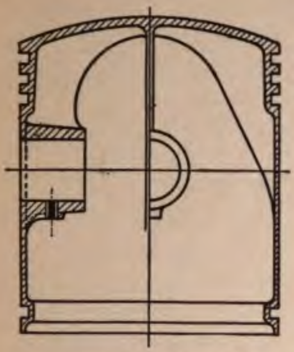


FIG. 79. Light-weight piston for Otto engine

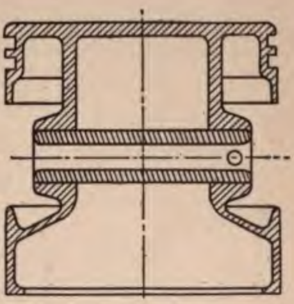


FIG. 80. The "zephyr" steel piston

dissipate excessive heat are shown, as are also two views of the wristpin bosses. In Fig. 80 is shown a "zephyr" steel piston.

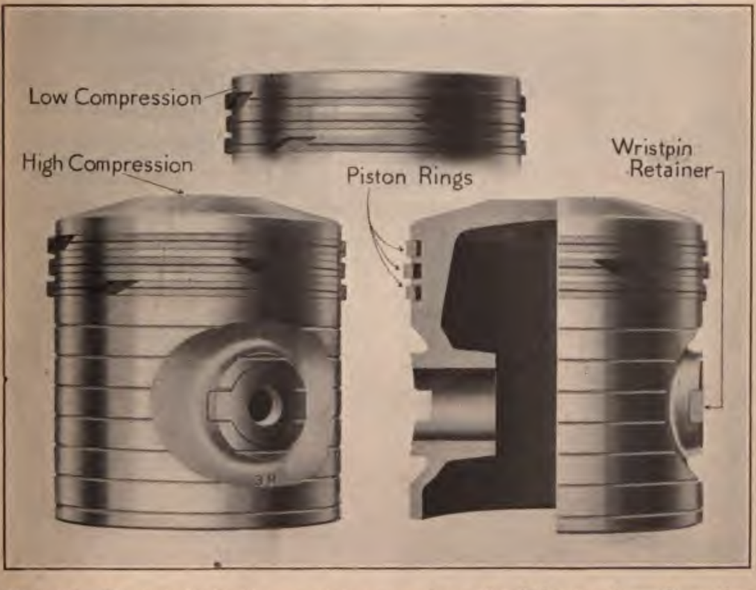


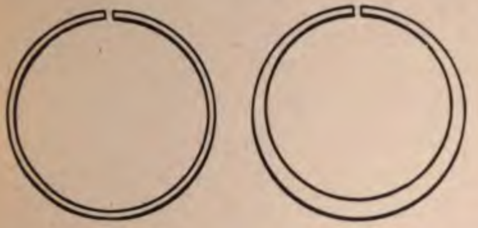
FIG. 81. Types of aluminum pistons used on the Liberty aircraft engine

One of its advantages is that the load on the piston head is more uniformly distributed than in the usual design, and this fact alone permits of lightening these parts. The wristpin is also considerably lighter, being not only shorter but also smaller in diameter. Fig. 81 shows the type of aluminum piston used on the Liberty and Hall-Scott aircraft engines. The piston shown in section has its crown slightly raised to permit of higher compression than the other. Note also the oil grooves cut in the piston to assist in lubricating the cylinder walls.

Piston Rings

In order that pistons may move freely up and down in the cylinder they must have a diameter less than the diameter of the cylinder bore. The amount of this freedom, or clearance, varies with the construction and type of the engine. It is obvious that if the pistons were not fitted with packing rings, the clearance would enable a portion of the gas to escape into the crankcase, thus destroying the efficiency of the engine. These packing rings, or piston rings as they are called, are usually made from cast iron and are split to permit springing them into suitable grooves machined on the exterior of the piston. Three or four of these rings are usually fitted on each piston of the Otto-cycle engine. On the Diesel-engine pistons the number is six or seven. This number is necessary on account of the higher compression used in the latter type of engine. Enough rings must be provided in each piston to achieve the requisite degree of gas-tightness under all running conditions; and contingencies, such as rings gumming up with carbon or breaking, must be provided for. An excessive number of piston rings increases needlessly the total engine friction, and so reduces the mechanical efficiency of the motor. Piston rings are made in two forms, as shown in Fig. 82. The ring shown at *A* is called the *concentric* ring, because the inner circle is concentric with the outer one and the ring is of uniform cross section at all points. The ring shown at *B* is called the *eccentric* ring; it is thicker at one part than the other. Theoretically the latter

type will make a tighter joint and its expansion due to heat is more uniform, but these advantages are not fully realized in practice. The eccentric ring must be cut at the point of least cross section. Experience has shown that concentric rings give better service, and that narrow rings, in a sufficient number, make a tighter packing with less friction than a smaller number of wider rings; also, two narrow rings in one groove give better results than one wide ring.



A, concentric piston ring

B, eccentric piston ring

FIG. 82. Two forms of piston rings

In Fig. 83 are shown the two forms of piston-ring joints, or cuts, in common use. The joint marked *A* is known as the lap joint, because the ends of the ring are cut in such a manner that they overlap. This is the better form of joint. At *B* is shown the diagonal cut. This joint permits the leakage of more gas than the lap joint, but is nevertheless widely used on small engines.

The rings must be of such a diameter and section as to give the desired pressure against the cylinder walls. The joints must not jam when expansion at full working temperature takes place, and yet they should reduce to a minimum the possibility of gas leakage. Uniform pressure around the circumference is an important item which can be achieved in practice only by careful foundry work on the original castings, so that internal stresses in the material may be minimized. After machining, the rings should be hammered so as to give this even pressure on the entire circumference of the cylinder walls.

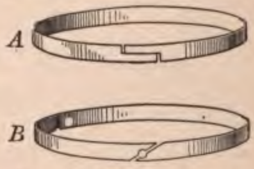


FIG. 83. Two common forms of joints in piston rings

Compression is one of the most important essentials to efficiency in internal-combustion engines. A leakage of compressed

gas during the compression stroke in a Diesel engine means that there may not be air enough within the combustion space to support combustion of the fuel. In the Otto-cycle engine there will be less than the normal quantity of mixture to burn. The power which the engine is capable of developing therefore falls off, the efficiency is reduced, and the fuel consumption per unit of power is increased. With leaky rings, loss of gas will of course occur during both the compression and expansion strokes, but most of the loss will take place during the expansion stroke.

Piston-ring leakage also has a very bad effect on the mechanism of the engine. The hot gas escaping past the piston rings destroys the lubricating oil film on the working surface of the cylinder and causes the piston to become unduly hot through the increased friction arising from this lack of lubrication. The hot gas flowing past the piston also heats it directly, and, furthermore, causes unsatisfactory working conditions of the wristpin bearing. The causes given may readily result in distortion and seizure of the piston, with the possibility of all the attendant consequences of a scored or cracked cylinder, damaged connecting rod, etc.

The quality of the metal of which the piston rings are made is, therefore, a matter of prime importance, no less than in the case of the cylinders and pistons. Steel for piston rings has been repeatedly tried, but without success. Cast iron is cheap and has peculiar properties of taking on, in use, an excellent surface for resisting wear under all conditions of rubbing contact, while giving the requisite degree of spring. There are few metals, however, which vary so much in quality as cast iron. The iron for piston rings should have a reasonably good tensile and high shock-resisting strength and have good wearing properties. The casting must be without flaws.

Wristpins

The wristpin, also called the piston pin, is a cylindrical metal part which is generally secured in bosses cast integral with the piston. The central portion of the pin has a bearing

in the small end of the connecting rod which is thus joined to the piston. The wristpins are generally made hollow. In small engines the wristpin and its bearing do not cause very much trouble. In large internal-combustion engines, however, the pin and its bearing are a source of more or less constant annoyance.

The pin must be prevented from moving lengthwise in the piston bosses. It must be securely locked in place, for if one of its ends should come in contact with the cylinder, it would soon cut the cylinder wall. The pin is usually fixed in the piston bosses so that the connecting rod alone will oscillate about the pin. In some designs the pin is allowed to rotate both in the bosses and in the connecting-rod bearing. The wristpin is made of steel.

The Connecting Rod

The connecting rod is the connecting link between the piston and the crankshaft. It consists of the rod proper, the small end which forms the bearing for the wristpin, and the large, or crank, end which forms the bearing for the crankpin. Connecting rods are almost invariably made of steel. In high-speed engines, where the reciprocating parts must be of the least possible weight, the rod is made either tubular or of I-beam or H-section.

Fig. 84. Connecting rod for a 2-cycle engine

In Fig. 84 is shown the connecting rod of a small 2-cycle marine engine. The rod is a drop forging of I-section. The crankpin end is fitted with babbitt-lined, removable brasses made in halves. Fig. 85 shows, partly in section, a Diesel-engine connecting rod from an engine delivering 30 horse power per cylinder. The weight of this rod is 165 pounds. The connecting rod shown in Fig. 86 is from an aircraft engine delivering about the same power per cylinder; it weighs about 10 pounds.

In V-type motors the connecting rods of two oppositely located cylinders are secured to the same crankpin. There are three possible ways of doing this: (1) The two connecting-rod ends may

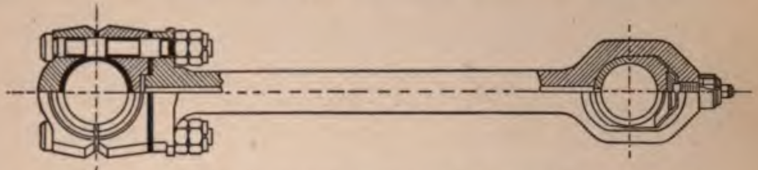


FIG. 85. Connecting rod for Diesel engine (weight, 165 pounds)

be located on the crankpin, side by side. This side-by-side arrangement, which necessitates a slight offsetting of the cylinders, is used on the Curtiss aircraft engines and on many automobile engines. (2) One rod may be forked and have its bearing on the outside of the crankpin bearing of the other rod, which is fitted to the crankpin.

FIG. 86. Connecting rod for aircraft engine (weight, 10 pounds)

This construction is used on the Liberty and other aircraft engines. (3) One connecting rod, known as the master rod, may have a bearing on the crankpin and be provided with a lug to which the other shorter rod is pivoted. This last arrangement is difficult to adjust for wear and hence is not widely used.

THE CRANKSHAFT

The crankshaft is one of the most vital as well as one of the most expensive parts of an engine. It is subjected to severe strains, and hence must be made of a suitable grade of steel correctly dimensioned and properly heat-treated. It is usually made hollow to reduce weight and insure homogeneity of material. The crankshaft is made up of the crankpins, crank-arms, crank-journals, and driving ends. Crankshafts are usually made

up from integral forgings, although built-up crankshafts are occasionally used on large engines to facilitate repairs or renewals.

Nearly all crankshafts, especially those employed in high-speed engines, are carefully balanced by applying counterweights to

Fig. 87. Balanced crankshaft for a 4-cylinder, 2-cycle marine engine

the crank-arms. If this were not done, the unbalanced centrifugal force would cause excessive vibration and severe stresses throughout the engine structure. The question of proper balance is of the most vital importance in aircraft engines.

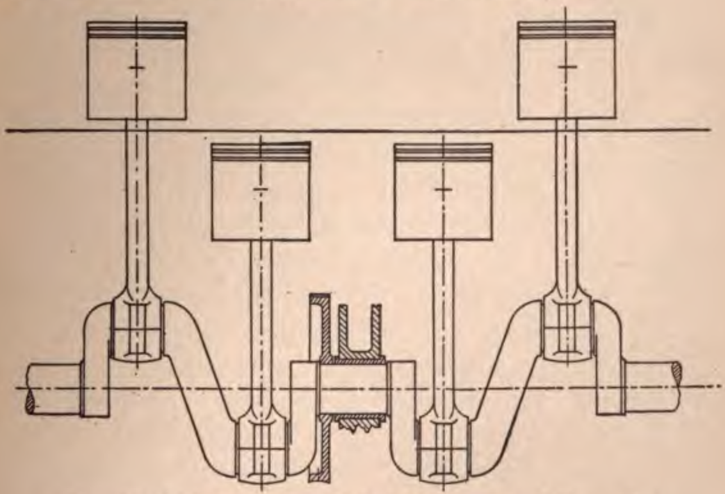


Fig. 88. Unbalanced crankshaft of an automobile engine

Several representative types of crankshafts are shown below. Fig. 87 shows a crankshaft for a 4-cylinder, 2-cycle marine engine. This shaft has five bearings, or points of support. The balancing weights are forged integral with the crank-arms, as shown. In Fig. 88 the crankshaft, piston, and connecting-rod

FIG. 89. Crankshaft for a 6-cylinder or 12-cylinder engine

assembly for a 4-cylinder automobile engine are shown. This shaft has but three bearings and is unbalanced. In Fig. 89 is shown a crankshaft for a 6-cylinder or 12-cylinder engine. This shaft is the type used on high-speed engines. It has seven bearings and is naturally and exactly balanced by the two sets of three cranks, each set being symmetrically arranged with cranks 120 degrees apart. This property of *natural* balance is a feature of crankshafts for 6-cylinder and 12-cylinder engines.

THE CAMSHAFT

The shafts for operating the irregularly shaped lugs, called cams, which operate the valve mechanisms, are known as camshafts. A cam is a lug integral with the camshaft and machined to a form resembling a circle, with an approximately triangular projection at one point. It is this projection which acts on the valve mechanism as the shaft rotates. The camshaft rotates at one half the engine speed.

The camshaft receives its motion from the crankshaft, from which all the accessories must be driven. These accessories include the igniting apparatus, water pump, oil pump, air pump, etc. There are several methods of driving the camshaft, the most common being by means of gearing or chain drive. These systems are employed where the camshafts run at one side of the crankshaft and parallel to it. Overhead camshafts are very generally used on aircraft engines having their valves in the head. When the camshaft is overhead, the drive for the shaft is by means of two pairs of bevel gears and a vertical intermediate shaft driven from the crankshaft.

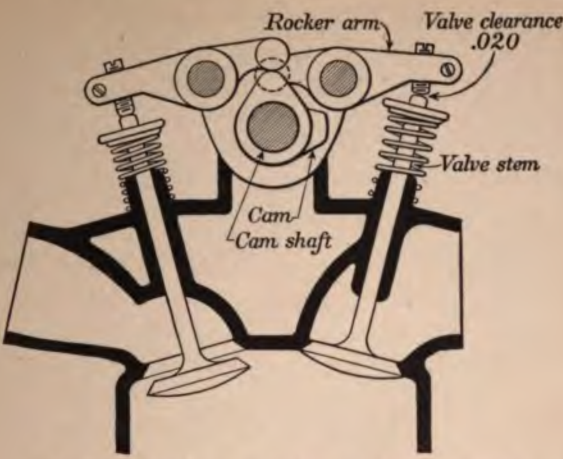


FIG. 90. Overhead camshaft with rocker arms

The accompanying figures show cams operating on overhead valves. In Fig. 90 the cams act direct on rocker arms attached to the overhead camshaft, and in Fig. 91 they act through the medium of tappet rods operated by a camshaft at one side of the crankshaft. As a general rule both inlet and exhaust valves are actuated by the same camshaft, although there are exceptions made, some engines having separate camshafts for inlet and exhaust valves.

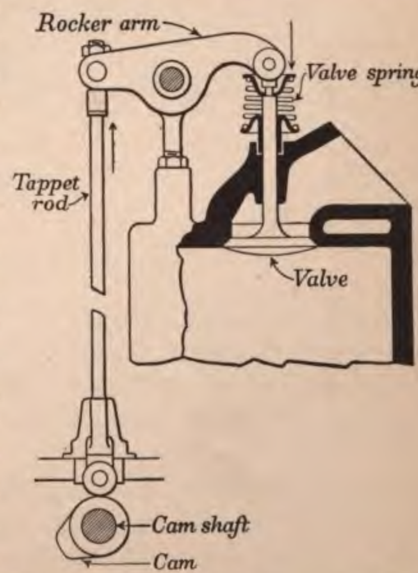


FIG. 91. Overhead valves operated by tappet rods from camshaft below

In Fig. 92 is shown the one-piece camshaft and overhead camshaft assembly of a Liberty 12-cylinder engine. There is one of these camshafts for each bank of six cylinders.

VALVES

The valves of modern internal-combustion engines are almost exclusively of the poppet type and are made of tungsten steel, which has the necessary high resistance to heat, is extremely hard, and is said to be nonpitting. A poppet valve is illustrated in Fig. 91 and consists of a disk of metal, with a stem on one side and coaxial with the disk. The valve is held against its

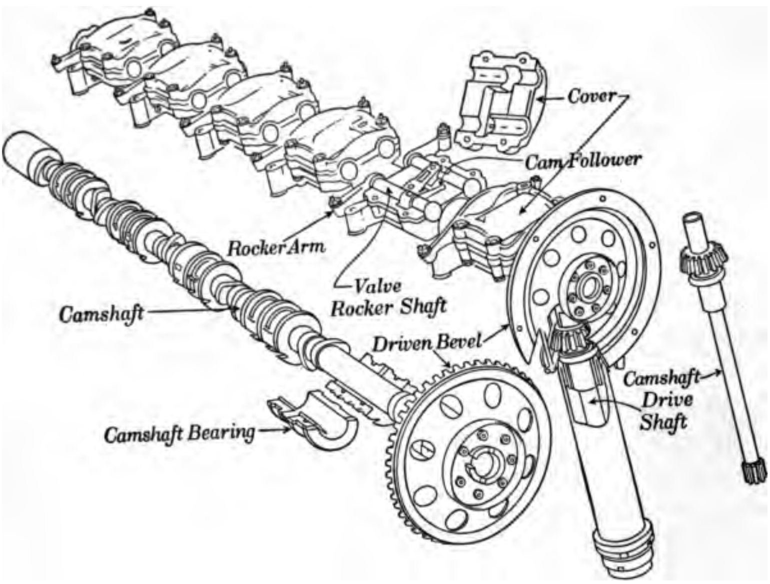


FIG. 92. Camshaft assembly of Liberty engine

seat by a spring. To open the valve, a force has to be applied in a direction indicated by the arrow contrary to the direction of spring pressure and strong enough to overcome the spring. Formerly the inlet valves were generally actuated by the suction prevailing in the cylinder during the inlet stroke, such valves being called automatic or suction valves. Automatic valves are now rarely employed in modern engines, owing to their rapid wear and to the low volumetric efficiency resulting from their use. Exhaust valves must of necessity be mechanically operated, and of late years mechanically operated inlet valves have been

used almost without exception. In addition to the poppet valves, sleeve, piston, and rotary valves may be used.

A sleeve-valve motor, introduced in 1908 by Charles Y. Knight, an American engineer, has proved most practical and satisfactory. One feature of the sleeve-valve is the elimination of the noises which are associated with the use of poppet valves. Another advantage claimed for the sleeve-valve motor, which perhaps is of more importance than the elimination of noises, is the increased flexibility and added power developed. This is due to the gain in volumetric efficiency resulting from the large gas passages which permit the fresh mixture to enter and the burned gases to leave without being impeded or restricted.

The principle of operation of the Knight engine does not differ materially from other internal-combustion engines of the 4-cycle type. In the top of each cylinder are two lateral slots which communicate respectively with the inlet and exhaust pipes. Within the cylinder bore, and interposed between it and the piston, are two thin cast-iron sleeves arranged so that they can be moved up and down by a suitable crankshaft and connecting-rod mechanism which is driven at one-half engine speed through a silent chain gearing. The sleeves are moved in such a way that the slots in the cylinder are opened and closed by the reciprocating movement of the sleeves. The openings in the sleeves are so wide that the gases enter and leave the combustion chamber with much more freedom than is possible through ports closed by valves of the poppet type.

With the poppet valves the best arrangement is obtained when both the inlet and exhaust valves are located in the cylinder head at an angle of about 30 degrees. This practice is followed in the design of the Liberty and many other aircraft engines, and is illustrated in Fig. 90. This is called the valve-in-head type. Motors with this valve arrangement gain flexibility, power, and efficiency by offering the least resistance to the entrance of the gas into the cylinder and to its escape therefrom after it is burned. The valve-opening mechanism, however, is somewhat more complicated than that used in the T-head or L-head

arrangement shown diagrammatically in Fig. 93. With the T-head arrangement, as shown at *A*, two separate camshafts are usually employed, and the valves are raised by direct-lift plungers.

The T-head arrangement is widely used in this country, for the reasons that large valves can be employed, a well-balanced and symmetrical casting can be obtained, piping may be placed without crowding, and larger manifolds can be fitted; furthermore, the valves may be easily removed and inspected without taking off the manifolds. The spark plug in this construction may be located directly over the inlet valve, where there is always a pure charge, and thus the ignition will be more certain when the engine is greatly throttled. This permits running the T-head motor at a lower idling speed than the other types. Considered from the theoretical point of view, the T-head type gives the worst form of combustion chamber and considerably lower efficiencies than either the valve-in-head or the L-head type.

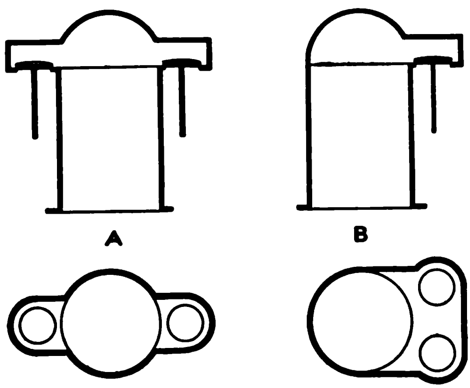


FIG. 93. *A*, T-head valve arrangement; *B*, L-head valve arrangement

The L-head arrangement, shown at *B*, calls for but one camshaft, the valves being lifted directly from their seats by a simple cam follower. The L-head arrangement of valves is widely used abroad and is coming more and more into use in this country on account of the gain in efficiency and power resulting from its use.

VALVE TIMING

Theoretically, the inlet valve should begin to open at the beginning and should close at the end of the inlet stroke, and the exhaust valve should open a trifle before the end of the expansion stroke. For satisfactory operation at high speeds,

however, it is necessary to alter the valve periods considerably. The exhaust valve must open earlier and close later, and the inlet valve must open later (in order not to overlap the exhaust opening) and close later. The respective lags and leads must be proportionately greater as the engine speed increases.

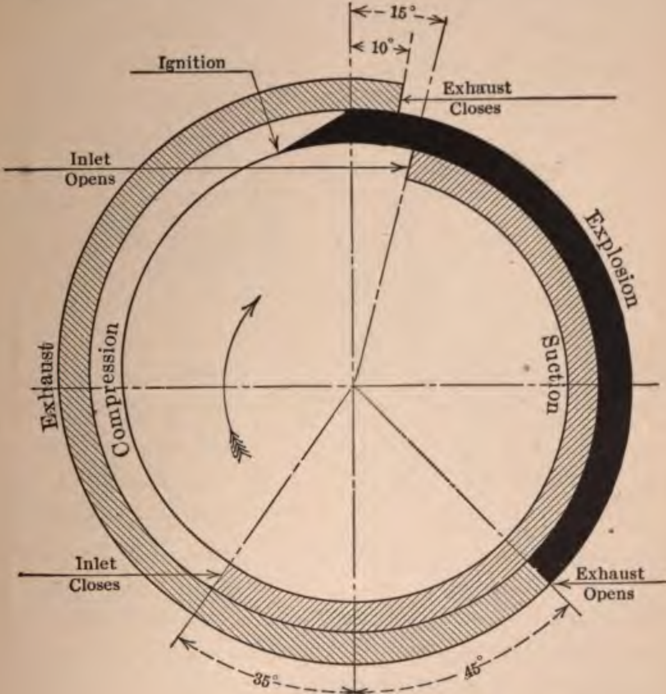


FIG. 94. Valve-timing diagram for average engines

That advancing the time of the opening of the exhaust valve was of value was discovered early in the art of internal-combustion engineering, and is explained by the necessity of releasing a large amount of gas, the volume of which has been greatly increased by the heat of combustion.

In ascending, on the exhaust stroke, the piston imparts a high velocity to the burned gases. If the exhaust valve is allowed to

remain open a short time after the piston starts downward on the next stroke, the inertia of the escaping gases is utilized to scavenge the cylinder in a thorough manner. If the inlet valve is left open during the first part of the compression stroke, the momentum of the inrushing gas serves to increase the charge in the cylinder to a maximum. If no lag were allowed in closing the inlet valve, less mixture would have time to enter, with the result that the power would fall off greatly at the higher speeds due to a decrease in volumetric efficiency. The timing of the valves, illustrating the above-mentioned principles for the average American engine, is shown diagrammatically in Fig. 94.

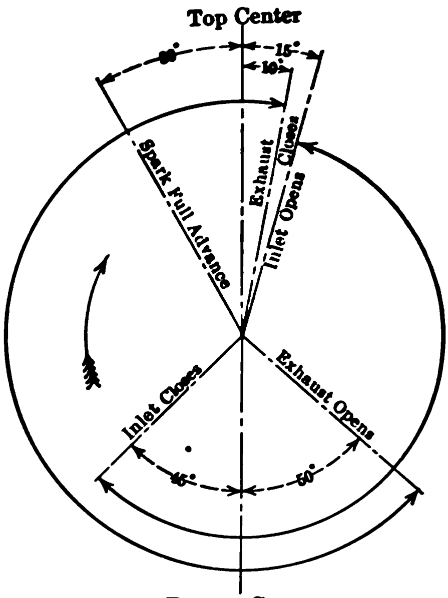


FIG. 95. Valve-timing diagram for engines of high speed

For engines running at high speed, like aircraft and racing engines, the timing may be made as illustrated diagrammatically in Fig. 95. Here the operation is as follows:

Exhaust opens 50 degrees ahead of bottom center.

Exhaust closes 10 degrees past top center.

Inlet opens 15 degrees past top center.

Inlet closes 45 degrees past bottom center.

It must be pointed out that if the valves are timed to give the best results at high speeds, the engine will not run so satisfactorily nor be so flexible at low speeds. Valves are usually timed, therefore, for the average operating conditions.

The Diesel Valve Group

The arrangement of the admission, exhaust, and fuel valves of a typical American Diesel engine is illustrated in Fig. 96. The figure shows the cylinder head containing a relief valve, while the admission, exhaust, and fuel valves are contained in a chamber at one side, similar to the L-head arrangement already described.

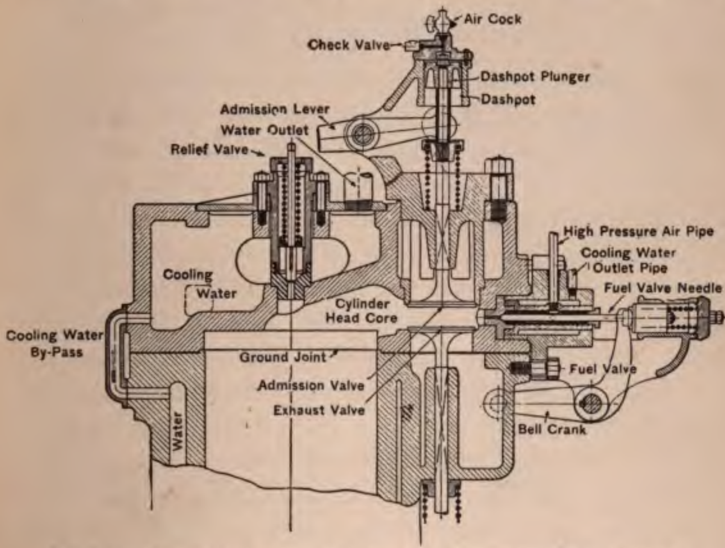


FIG. 96. The valve group of a typical American Diesel engine

It will be noted that both admission and exhaust valves are of the simple poppet type, the admission valve working downward and the exhaust valve working upward. The admission and fuel valves are held in separate cages, so that the seats may be easily cared for. The relief valve in the center of the head is usually set to open at about 800 pounds per square inch and acts as a safety valve against undue pressure caused by premature ignition, which may occur in case the fuel valve sticks or leaks.

The fuel-admission valve is opened by the bell crank, shown in Fig. 96, which pushes the needle to the right against the spring and opens the valve. This occurs about the time the

piston reaches the end of the compression stroke. Highly compressed air then rushes through the perforated washers where the oil is atomized, and forces the oil into the compressed cylinder charge. Water is circulated in the space between the steel bushing and the walls of the valve cage, in order to keep the needle valve cool and prevent the oil from carbonizing in the atomizer.

Flywheel

The function of the flywheel is to minimize the fluctuation of the engine speed, caused by the variation of crank effort and by the variation in the load upon the engine, by storing up the mechanical energy developed during the power stroke.

Flywheel weight is dictated largely by the number of cylinders employed, it being a general rule that engines having the least number of cylinders require the heaviest flywheels. Flywheel weight is also determined by many other conditions, some of the important ones being the bore of the cylinder, the speed of crankshaft rotation, the degree of compression, and the use for which the engine is designed. In 4-cylinder and 6-cylinder engines the flywheel is usually made larger than is required by the running conditions, because it facilitates the starting of the motor. Without a flywheel it would be impossible for the operator of average strength to turn the crankshaft of a motor larger than 5-inch bore against compression.

Mufflers

The pressure of the gases in the cylinder of an internal-combustion engine is still high enough when the exhaust valve opens to cause them to escape with a loud explosive sound. Some provision is generally made for deadening or silencing the sound of the exhaust. The apparatus for accomplishing this is known as the muffler.

An efficient muffler not only deadens the sound of the exhaust but also offers a minimum resistance to the escape of the gases.

Any resistance to the escape of these gases causes a back pressure against the piston of the engine during the exhaust stroke, and thus reduces the efficiency of the engine and decreases the amount of power it will develop. In the muffler the gases must be allowed to expand gradually and to cool, thereby reducing the pressure which is the cause of the noise when they are discharged into the atmosphere directly.

There are many efficient mufflers on the market, among them the ejector muffler, the gas-pipe muffler, the Thompson muffler, the concentric-cylinder muffler, the small-tube muffler, and the baffle-plate muffler. In marine mufflers the cooling water from the cylinders is generally used to assist in reducing the temperature of the exhaust gases.

A cut-out, or relief valve, is frequently provided between the exhaust manifold and muffler. This valve is opened when the maximum power that the motor will develop is desired. The cut-out valve is also valuable because it permits one familiar with internal-combustion engines to detect irregularities in the engine operation by the sound of the exhaust.

CHAPTER XIV

AIRCRAFT ENGINES

The realization of sustained mechanical flight is due entirely to the development and refinement of a reliable, light-weight, high-powered internal-combustion engine. The solution of the problem of flight would undoubtedly have been attained long before it was if the proper source of power had been available, as all other essential problems of aëronautics had been solved previously. Nearly all aircraft engines are water cooled, 4-cycle engines using gasoline for fuel.

The principal requirements of an aircraft engine are (1) great power output for weight with a good factor of safety, (2) reliability of operation under flying conditions, (3) economy and efficiency, (4) safety from fire, and (5) accessibility of all parts to permit of their adjustment, repair, and renewal.

1. The engine weight per horse power must be kept at the lowest possible value in order (*a*) to be able to climb rapidly, so as to clear the earth within as restricted a distance as possible and, in warfare, to enable the machine to remove itself quickly beyond range of the enemy guns or to get above the hostile aëroplanes; (*b*) to reduce the gross weight and thus improve the gliding angle, thereby permitting the pilot to alight safely within a restricted area; (*c*) to increase safety when flying in a high wind; (*d*) to enlarge the radius of action of the machine and so avoid frequent replenishments of fuel and oil; and (*e*) to give as wide a range of flying speeds as possible.

2. Aircraft engines must be reliable, since flight can be maintained in such an unstable medium as air only as long as the power plant is functioning properly. Proper functioning demands dependable lubrication, uniform power delivery, good mechanical balance, and certainty of operation.

3. Economy in the consumption of fuel and oil and maintained efficiency under all conditions are necessary in order to give that large radius of action which is now demanded of aircraft, and which has made the Atlantic flight an accomplished fact.

4. Safety from fire is attained by good design and by the proper protection of the fuel supply by suitable materials which have been developed for this purpose.

5. Accessibility of all parts is necessary because high-speed aircraft engines require comparatively frequent dismantling and the renewal of worn parts, and a considerable amount of careful, skilled attention in order to keep them in a satisfactory running condition.

The most important types of aircraft engines may be classified as the diagonal, or V, type, the vertical, and the rotary. Of these the latter type has been discontinued in the military service in this country, although it is still widely used abroad, particularly in planes of French design.

The Diagonal, or V, Type

Under this head comes the now justly famous Liberty 12-cylinder engine shown in Fig. 97, as well as the Curtiss, Hall-Scott, Hispano-Suiza, and other engines used by the American and Allied armies and navies during the recent World War.

The following, based on a statement issued by the War Department, describes in detail the development of the Liberty engine: The designers of the cylinders of the Liberty engine followed the practice used in the German Mercedes, English Rolls-Royce, French Lorraine-Dietrich, and Italian Isotta-Fraschini before the war and during the war. The cylinders, which are free to expand equally in all directions, are made of steel inner shells and surrounded by pressed-steel jackets. An American automobile firm, by long experiment, had developed a method of applying these steel water jackets. Individual and interchangeable cylinders are used throughout.

In the Liberty the included angle between the cylinders is 45 degrees; in all other existing 12-cylinder engines it is 60 degrees. This feature is new with the Liberty engine and

was adopted for the purpose of bringing each row of cylinders nearer the vertical and closer together, so as to save width and head resistance. By the narrow angle greater strength is given to the crankcase, and vibration is reduced.

The pistons of the Liberty engine are of the Hall-Scott design shown in Fig. 81. In Figs. 98 and 99 are shown end sections of the Liberty motor. The long raised-crown piston, shown in section in Figs. 81 and 98, is used in the army engines, which have higher compression and consequently greater power than the engines used for the navy. The horse power developed in the low-compression engine ranges from 375 to 400, while that of the high compression is from 425 to 450. The weight of each of these engines is approximately 825 pounds, and the maximum speed from 1650 to 1800 revolutions per minute. The bore and stroke of the Liberty engine are 5 and 7 inches respectively. The compression ratio for the navy Liberty is about 4.9 and for the army Liberty about 5.6.

The valve cages, which may be seen in Fig. 98, are drop forgings welded to the cylinder head. The principal departure from European practice is in the location of the holding-down flange, which is several inches above the mouth of the cylinder; and in the unique method of manufacturing the cylinders from steel tubing.

The design of the camshaft and valve mechanism above the cylinder heads is based on the Mercedes, but was improved by American engineers for automatic lubrication without wasting oil. The camshaft drive was copied almost entirely from the Hall-Scott motor. This type is used by the Mercedes, Hispano-Suiza, and others.

The generator battery ignition system used on the Liberty has been previously described. It was especially designed to save weight and to meet the special conditions due to firing two banks of 6 cylinders with an included angle of 45 degrees.

The forked, or straddle-type, connecting rods, which have been previously described, are used. The crankshaft design

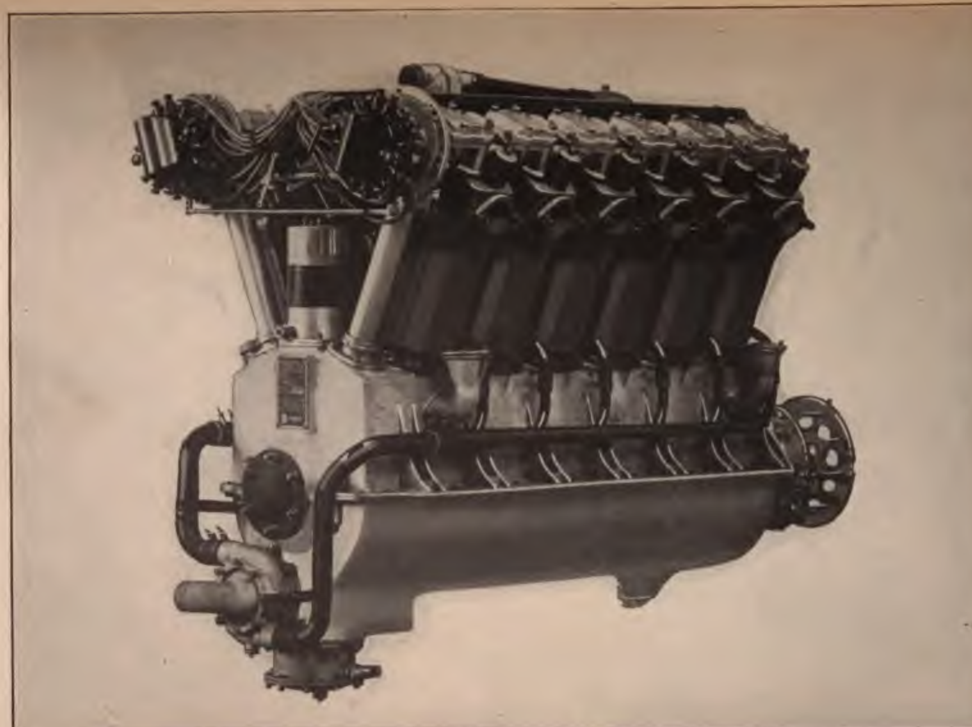


FIG. 97. The Liberty engine

follows the standard 12-cylinder practice, except as to oiling. The crankcase follows the standard practice. The 45-degree angle

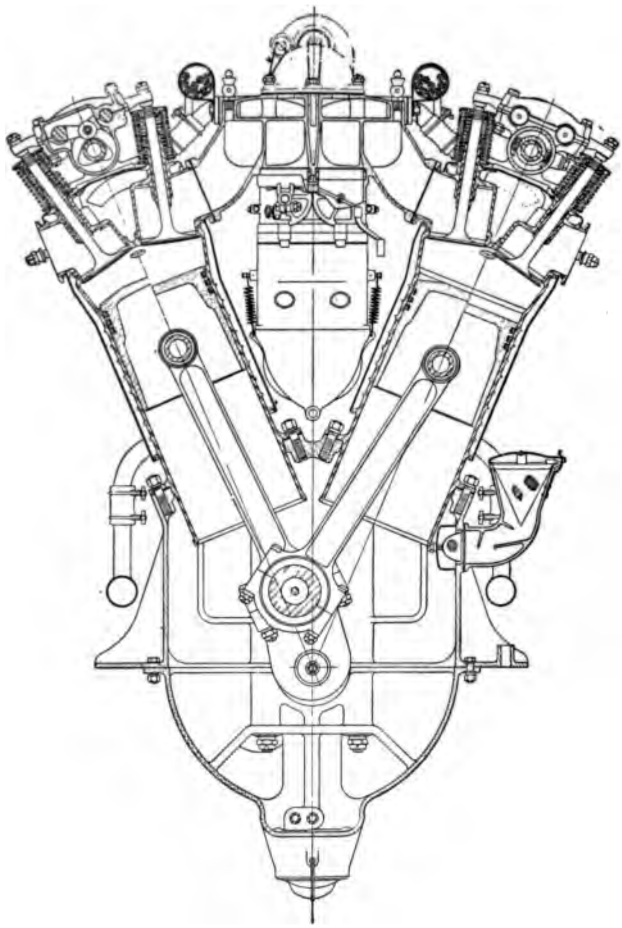


FIG. 98. End section of Liberty engine showing types of pistons used for different compression ratios

and the flange location on the cylinders make possible a very strong box section.

The first system of lubrication followed the German practice of using one pump to keep the crankcase empty, delivering

into an outside reservoir, and another pump to force oil under pressure to the main crankshaft bearings. This lubrication system also followed the German practice in allowing the overflow in the main bearings to travel out along the face of the

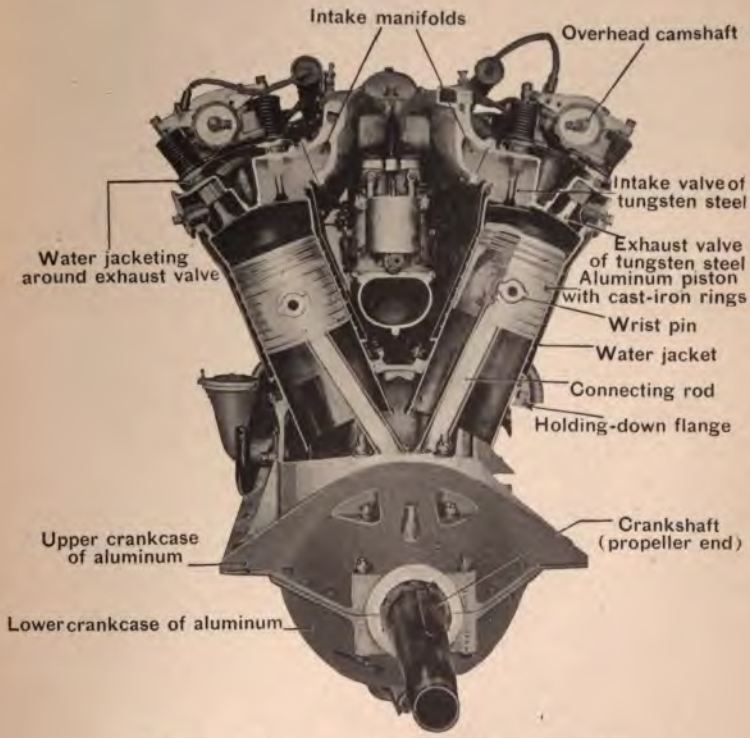


FIG. 99. End section of Liberty aircraft engine

crank cheeks to a scupper which collected the excess for crankpin lubrication. This system is very economical of oil and is still the standard German practice.

The present system of lubrication is similar to the original practice, except that the oil, while under pressure, is not only fed to the main bearings but is fed through holes inside the crank-cheeks to the crankpins also, instead of feeding these crankpins through scuppers. The difference between the two

oiling systems thus consists in carrying oil for the crankpins through the hole inside the crank-cheek, instead of up the outside face thereof.

The idea of developing Liberty engines of 4, 6, 8, and 12 cylinders with the above characteristics was first conceived about May 25, 1917. The idea was developed in conference with representatives of the British and French Missions and was submitted in the form of sketches at a joint meeting of the Aircraft (Production) Board and the Joint Army and Navy Board, June 4. The first sample was an 8-cylinder model, delivered to the Bureau of Standards, July 3, 1917. The 8-cylinder model, however, was never put into production, as advices from France indicated that demands for increased power would make the 8-cylinder model obsolete before it could be produced.

Work was then concentrated on a 12-cylinder engine, and one of the experimental engines passed the 50-hour test, August 25, 1917. The official report of August 25, 1917, records that "the fundamental construction is such that very satisfactory service with long life and high order of efficiency will be given by this power plant, and that the design has passed from the experimental stage into the field of proven engines."

In Fig. 100 is shown a cutaway view of the Liberty 12-cylinder engine exposing the crankshaft, camshaft, overhead camshaft assembly, oil pump and sump, connecting rods, etc.

The following additional characteristics complete the description of the 12-cylinder Liberty engine:

Cooling. Water circulated by a high-speed centrifugal pump, water temperature at outlet 170° F. and not to exceed 200° F.

Lubrication. Forced-feed dry sump, external oil reservoirs. Capacity, 13 gallons. Oil pressure varies between 20 pounds and 50 pounds. Oil temperature desired, 130° F.

Carburetion. Two Zenith duplex carburetors.

Idling speed. 650–800 revolutions per minute.

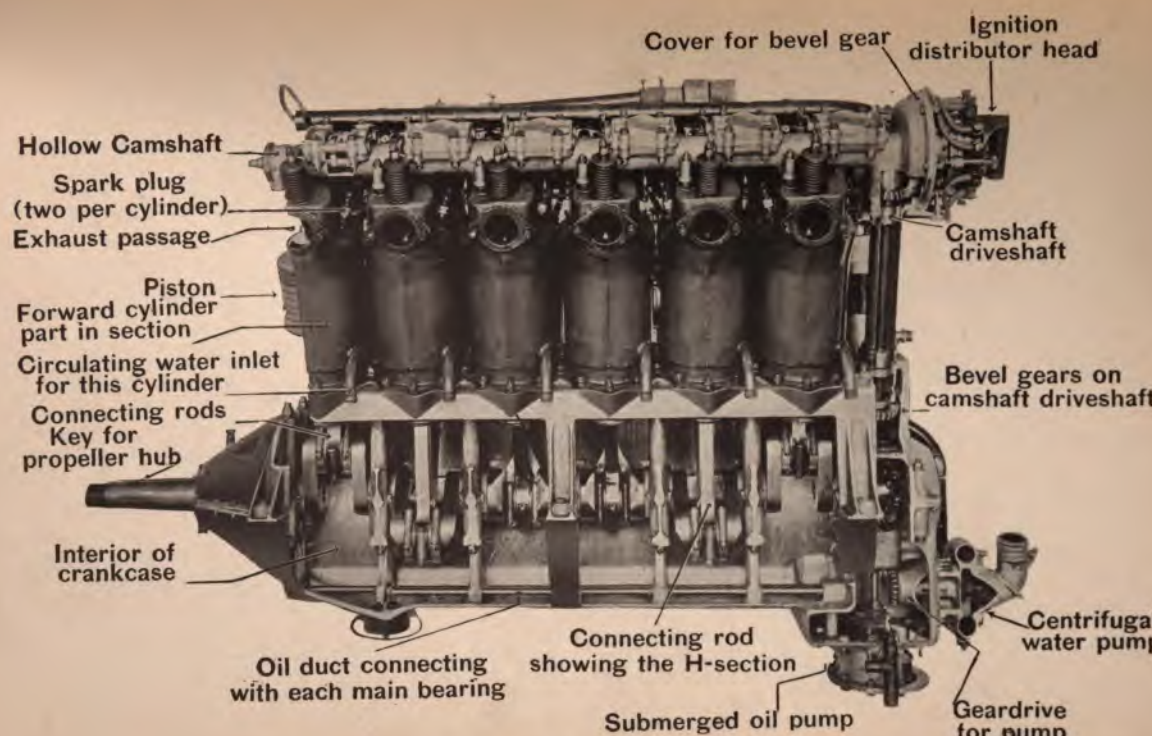


FIG. 100. Cutaway view of the Liberty engine

Valve timing.
- Intake opens 10 degrees past top center.
- Intake closes 45 degrees past bottom center.
- Exhaust opens 50 degrees before bottom center.
- Exhaust closes 10 degrees past top center.

Firing order. 1L–6R–5L–2R–3L–4R–6L–1R–2L–5R–4L–3R– (numbers refer to the number of the cylinder, beginning with No. 1 forward, and "L" and "R" refer to the left-hand and right-hand cylinder banks respectively).

Hall-Scott Engine

A side view of the Hall-Scott 12-cylinder V-type engine assembled is shown in Fig. 101, and in Fig. 102 is shown a sectional view of the end of the same type of engine. This engine, like the Liberty, uses an individual, interchangeable cylinder, the same piston, a similar 7-bearing crankshaft, overhead camshaft assembly, and the same size cylinder bore and stroke. There are also many other points of similarity between the two engines. The compression ratio of this engine, however, is greater, being about 6 and the horse power about 450. The angle between the cylinders is 60 degrees. The weight of this engine is approximately 1000 pounds.

Hispano-Suiza Engine

In Fig. 103 is shown the front view of an 8-cylinder, 300-horse-power, V-type Hispano-Suiza engine. There are two blocks of four cylinders each set at an angle of 90 degrees. The good streamline effect, which is a feature of this engine, is obtained by the block construction of the water jackets and the method used in housing the camshafts.

This type of engine differs very materially from those above described. The individual cylinders are steel forgings, heat-treated, machined, and threaded on the outside. These steel sleeves are flanged at the bottom and closed at the top; this surface, being flat, provides for the two valve seats. The cylinders are screwed into the cast aluminum cylinder blocks, which

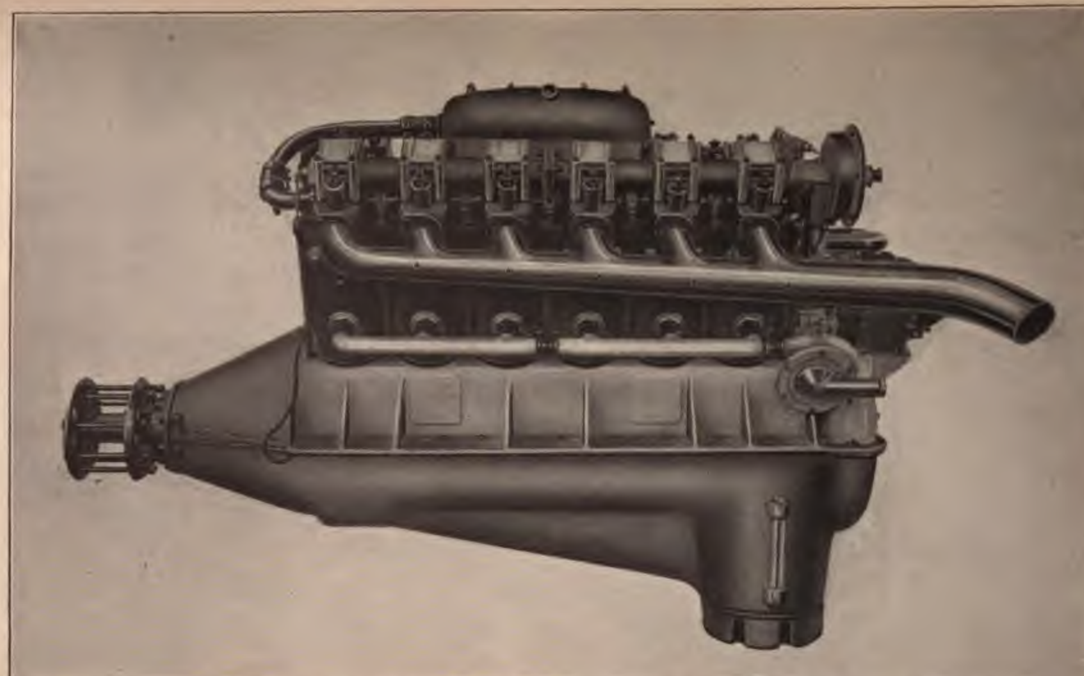


FIG. 101. Side view of the Hall-Scott 12-cylinder aircraft engine

form the water jackets and valve ports, as well as the intake and exhaust passages. The construction may be seen by reference to Fig. 104, which shows the engine, partly in section.

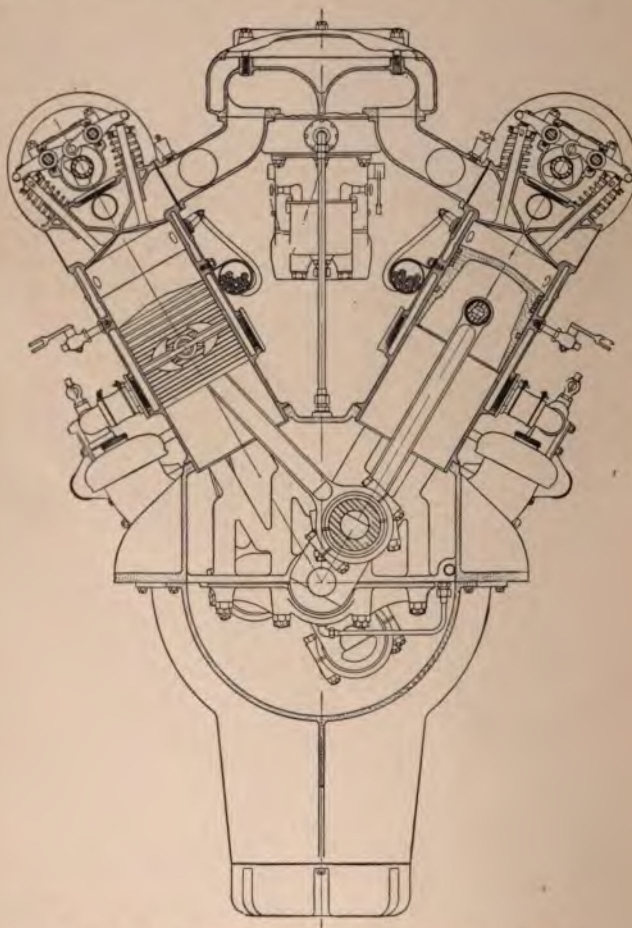


Fig. 102. End view of Hall-Scott 8-cylinder engine

The pistons are aluminum castings, three eighths of an inch in thickness at the head. The sides taper down from three eighths of an inch in thickness at the top to one eighth of an inch at the bottom. By this construction the heat is rapidly

carried off. At the top of each piston there are four narrow rings in two grooves. Near the bottom there is one small oil ring.

The connecting rods are heat-treated steel, tubular in section. One rod is forked at the bottom, having a two-piece bronze box, babbitt lined, bolted to it by four bolts. This bears directly on the crankshaft. The other rod bears on the outer and central portion of the bronze box.

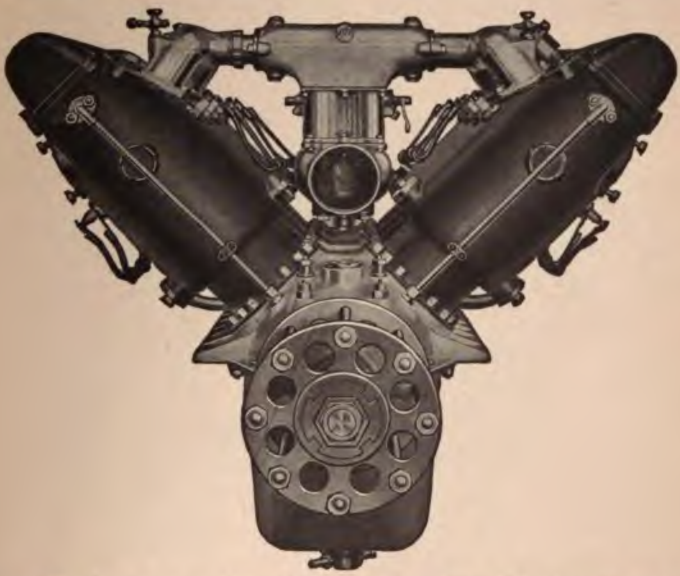


FIG. 103. Front view of the Hispano-Suiza, Model E, aircraft engine, showing streamline effect

The crankshaft is of the 4-throw type, 180 degrees between throws. It is made of chrome nickel steel, machined all over, and is made hollow for the sake of lightness and so as to allow the lubricating oil to get from the main bearings to the connecting-rod bearings. The propeller thrust is provided for by a double-row ball thrust bearing located in the front of the crankcase.

The valves, which in the Liberty are set at an angle of 30 degrees, are here set vertically in the cylinders along the

center of each block and are directly operated by a single superimposed camshaft. The camshafts are driven in nearly the same way as on the Liberty and Hall-Scott, but no rocker arms are used. The valve timing is very nearly the same as for the Liberty, except that on this model the spark occurs at about 25 degrees before top center.

Ignition is furnished by two Dixie magnetos, which are mounted at the rear end of the crankcase and are driven at crankshaft speed; and carburetion is secured by a Stromberg airplane carburetor.

The lubrication of the engine is provided for by a force-feed system, which in general is similar to that used on the Liberty engine. A sliding-vane type of pump is mounted vertically just below the rear end of the crankshaft in the lower half of the crankcase and delivers oil under pressure up to 60 pounds. It is driven by the same beveled gear on the crankshaft that drives the vertical shafts.

The vane pump forces oil through a filter provided with a removable screen, in the lower half of the crankcase, and then, through steel tubes cast in the lower crankcase, to three of the main bearings. From these bearings the oil enters the hollow crankshaft and is distributed to the four crankpins. Proper oil holes are provided in the inner connecting rods to distribute the oil to the outer connecting rods. The oil is then thrown off in the form of spray and, together with the oil thrown from the main bearings by the crankshaft, provides lubrication for the cylinders, pistons, and piston pins.

The fourth, or front, main bearing has a by-pass and is also provided with an oil lead from the system, which takes care of the lubrication of this bearing. Through the by-pass around the outside of the bearing it leads to tubes running up the front end of each cylinder block. This provides lubrication for the camshafts, camshaft bearings, cams, valve tappets, valve stems, vertical shafts, driving gears, etc.

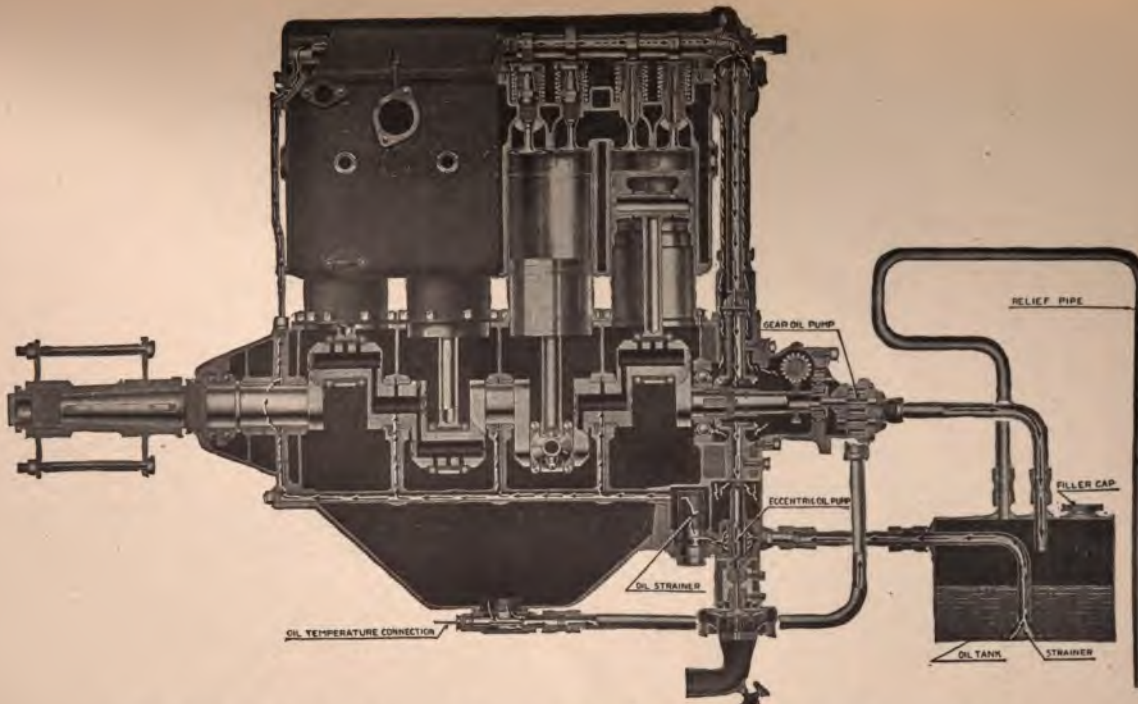


FIG. 104. Longitudinal view of Hispano-Suiza, Model E, engine, showing construction

THE CURTISS ENGINE

Except for the Liberty, the Curtiss engines are probably the most widely known of any in the American field of aviation. The Model OX, 8-cylinder, V-type, having a 4-inch bore and a 5-inch stroke, is the army model. The Model OXX used by the

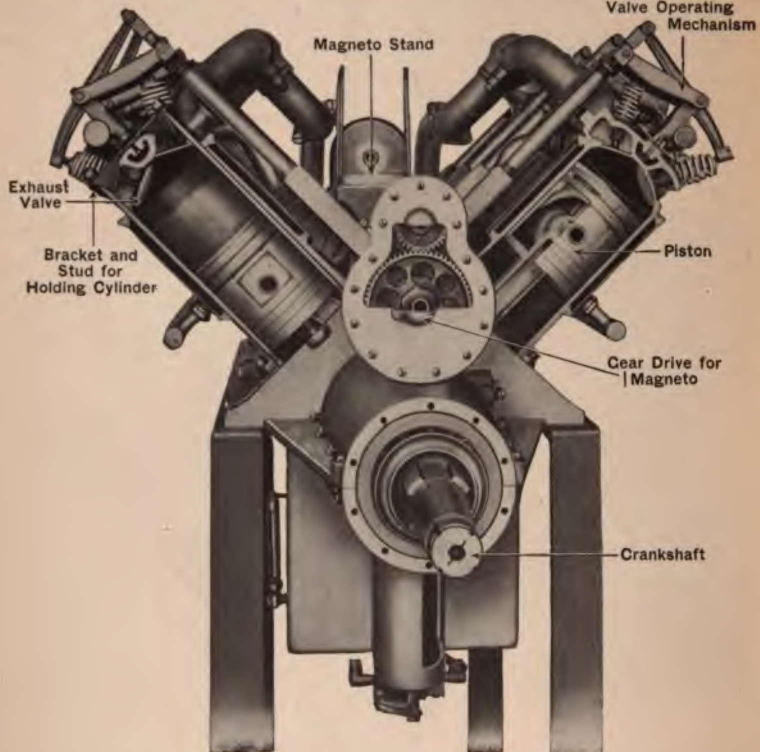


FIG. 105. The Curtiss 8-cylinder aircraft engine

navy differs from the OX principally in that its bore is $4\frac{1}{4}$ inches. In Fig. 105 is shown an end view of the OXX-type engine, revealing the piston in section, the valves in the head, the valve-operating mechanism, the geardrive for the magnetos, and the general assembly.

The cylinders of this engine are of steel surrounded by water jackets of Monel metal brazed on. The outside of the cylinder

is heavily nickel plated to prevent rusting. The cylinders are bolted to the crankcase by eight nickel-steel, heat-treated studs, four of which extend to the top of the cylinder, where they are fastened to a bracket, as shown in Fig. 105. This method of attaching the cylinders differs materially from those described in the above-mentioned types of engines. The angle between the cylinder banks is 90 degrees.

The valve-operating mechanism is also quite different. Only one camshaft is used, and this is located in the crankcase. The valves are set at an angle in the cylinder head and are actuated by an ingenious arrangement of rocker arms and push rods.

The connecting rods are of steel, heat-treated and of H-section. They are placed side by side on the crankpin. This necessitates having one bank of cylinders ahead of the other.

Carburetion is provided by a Zenith duplex carburetor, and ignition by two Dixie magnetos located at each end of the crankcase between the cylinder banks.

The Vertical Engine

In Fig. 106 is shown a longitudinal section, and in Fig. 107 is shown an end section, of a Hall-Scott, vertical, 6-cylinder aircraft engine designed for advanced training, single combat, and scout machines. The cylinders are similar to those used on the Liberty engine and have the same 5-inch bore and 7-inch stroke. The compression ratio is 6.55; the rated horse power is 200, and the normal brake horse power is 215 at 1700 revolutions per minute. The weight per brake horse power is 2.3 pounds. The valves, pistons, connecting rods, crankshaft, camshafts, valve mechanism, and the cooling and lubricating systems are similar to those used in the Liberty engine.

Carburetion is secured through two specially designed carburetors and twin manifolds, which are of the hot-water-jacketed design. The carburetors are interconnected through a control rod, part of which may be seen in Fig. 106.

Ignition is secured through a specially designed generator-battery unit. The twin distributors are mounted on the end

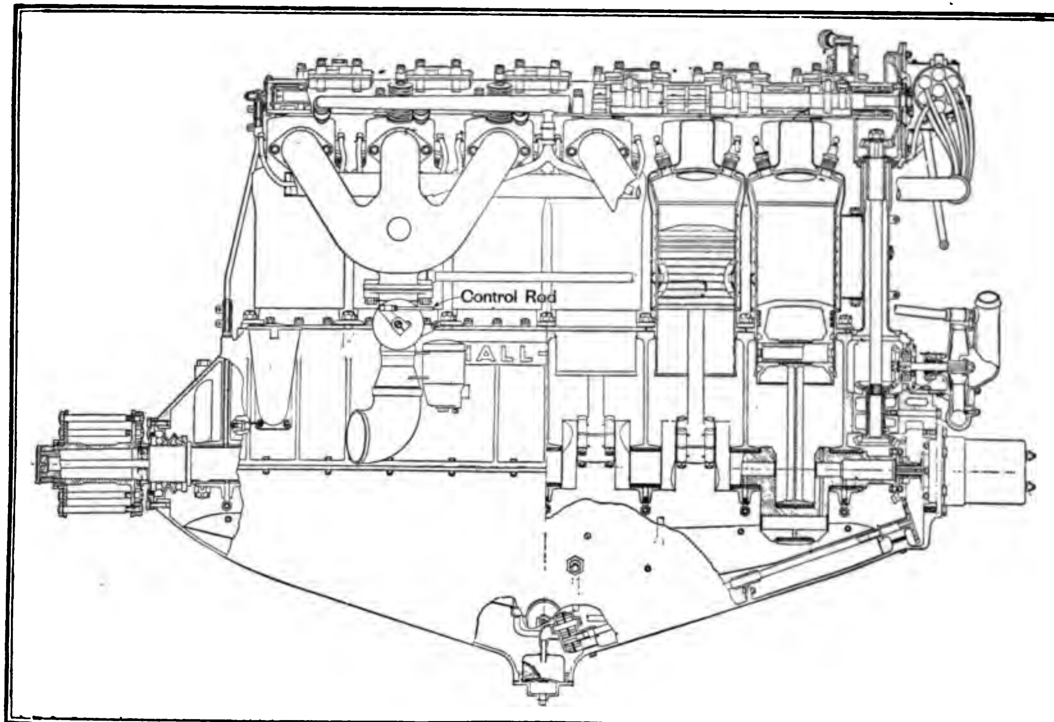


FIG. 106. Longitudinal section of a 6-cylinder aircraft engine

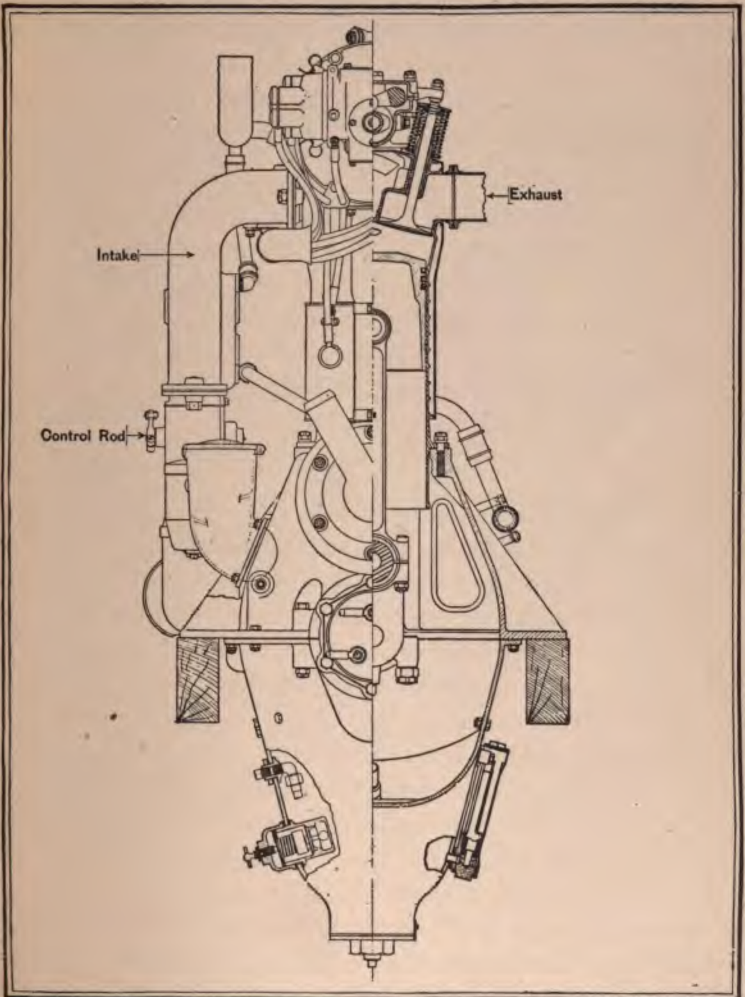


FIG. 107. End section of a 6-cylinder aircraft engine

of the camshaft housing and are driven off the camshaft. The coils are mounted directly underneath the distributors on the vertical shaft housing. The generator is bolted to the crankcase and is driven by suitable gearing connected to the crankshaft.

The Union Engine

Another vertical, 6-cylinder aircraft engine is the Union. This engine is used for the motive power of the navy dirigibles. It has many of the standard characteristics of the Liberty engine, including the valves in head, overhead camshaft assembly, H-section connecting rod, steel cylinders, aluminum pistons, water cooling, etc. The ignition is secured by two Dixie magnetos and carburetion by two Zenith carburetors. The cylinder bore and stroke are smaller than in the Liberty engine.

Rotary Engines

A rotary engine is one in which the crankshaft is *fixed* and the cylinders, crankcase, and attachments rotate around the crankshaft. A three-quarter view of a 9-cylinder, 130-horsepower, rotary engine complete is shown in Fig. 108. In external appearance the rotary aircraft engine resembles the radial engine. In the radial engine, however, the cylinders are stationary and the crankshaft rotates.

The rotary engine has proved itself very useful largely by reason of its lightness, the absence of reciprocating parts, and the steadying influence of the large rotational inertia obtained by having the cylinders rotate. These advantages are offset, however, by certain drawbacks. The engine must necessarily be air-cooled, and while the rapid motion of the cylinders increases the effectiveness of air-cooling, there is little doubt that, especially for prolonged flights, a water-cooled motor is preferable. Furthermore, the resistance of the air to rapid rotation of the cylinders absorbs fully 10 per cent of the power developed, while it is difficult to provide that uniform cooling of the cylinders which is necessary to avoid distortion. The leading surfaces of the cylinders tend to keep [illegible] lowing surfaces.

It has also proved very difficult to arrange satisfactorily for the supply of carbureted mixture to the several cylinders of this type of engine, and the result is an excessive consumption of fuel.

The lubrication of this engine has proved a difficult problem, the only solution being a profuse supply of oil, resulting in

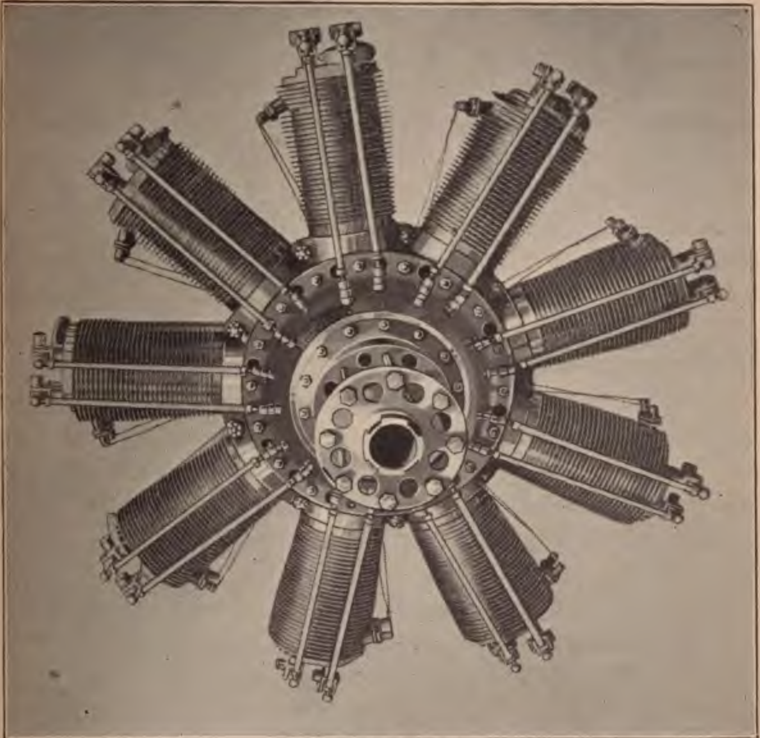


Fig. 108. A 9-cylinder rotary engine

an extremely high oil consumption. To avoid overheating, the largest practicable air-cooled cylinder must be less than 5 inches in bore, so that high power is attainable only by increasing the number of cylinders. This results in a corresponding increase in the number of parts and in general complexity.

The rotary engine is not used in the American field of aviation, although it has long enjoyed great popularity among British and French aviators, notwithstanding its drawbacks.

CHAPTER XV

ENGINES FOR MARINE AND AUTOMOBILE USES

The internal-combustion engine has acquired great success in its application for marine power. At present it is used for the propulsive power of heavy-duty motor launches, racing boats, submarines, submarine chasers, cargo and fuel ships, etc. Marine engines are very much heavier per horse power than either automobile or aircraft engines.

One of the most successful small engines for motor launches is the 2-cycle, 3-port gasoline engine which was developed by the Bureau of Steam Engineering of the United States Navy Department to meet the exacting requirements of the naval service. A sectional view of this engine is shown in Fig. 109. These engines are built with 1, 2, 3, or 4 cylinders, and are rated 5, 10, 15, and 20 horse power, respectively, at five hundred revolutions per minute. The cylinders are 4.5-inch bore and 5-inch stroke.

In design, particular attention has been paid to simplicity, accessibility, and wearing qualities. All parts are easily accessible for examination and repair, and parts subject to wear are so constructed that they can be renewed at a very small cost.

The cylinder, piston, and piston rings are made of a special grade of cast iron. The cylinder heads are removable and, together with the cylinders, are adequately water-jacketed. The pistons and rings for all engines are interchangeable. The connecting rods are drop forgings of steel and of I-section. The crankshaft, which is illustrated in Fig. 87, is a drop forging of special carbon steel and is well balanced.

Ignition is secured by the use of a Bosch high-tension magneto, and carburetion by a Schebler, Model D, carburetor

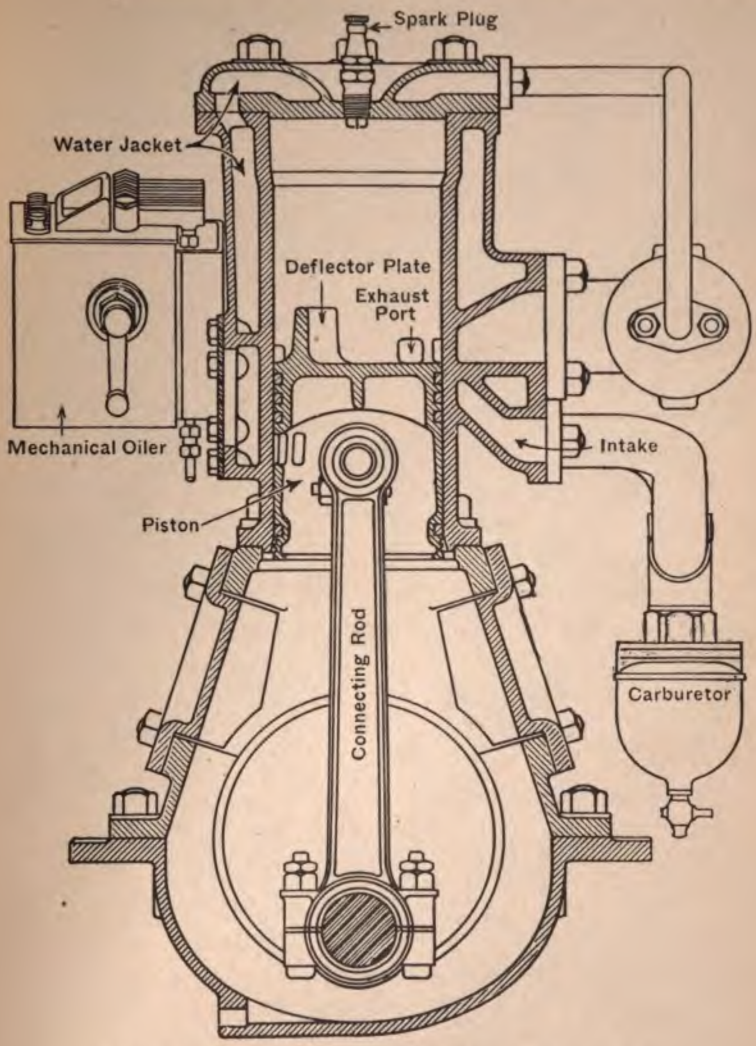


FIG. 109. A 2-cycle, 3-port low-speed marine engine

located as shown in Fig. 109. Lubrication is accomplished by force-feed mechanical oilers, grease cups, and the splash in the crankcase. The engine is reversed by a special hand reversing gear similar to that used on many commercial engines.

A High-Speed Marine Engine

In Fig. 110 is shown an end view, half in section, of the Van Blerck 4-cycle high-speed marine engine. This engine is

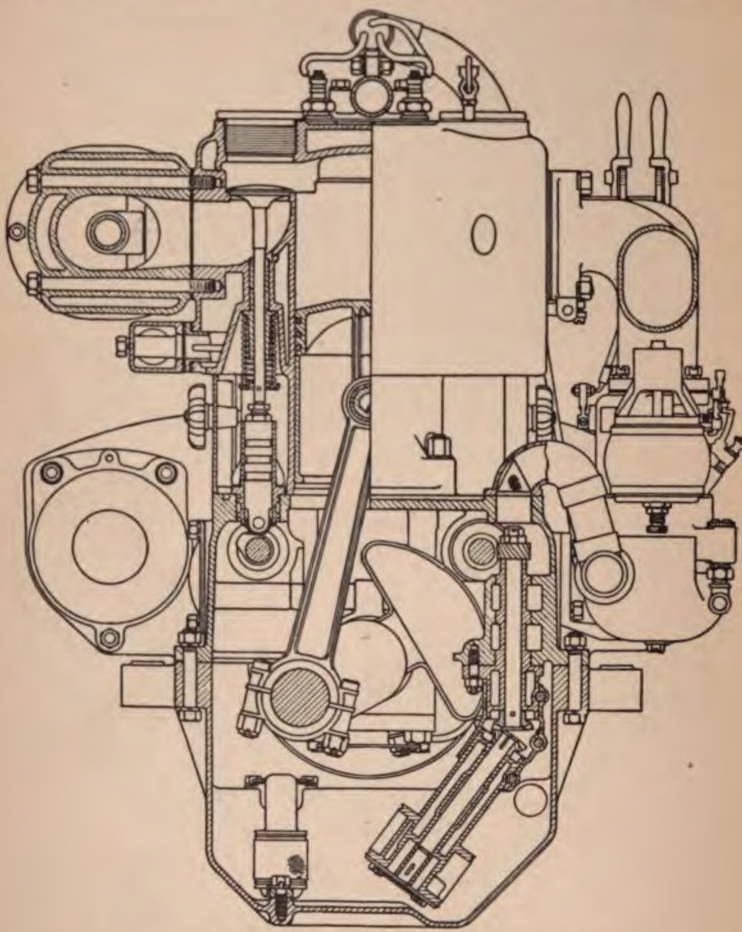


Fig. 110. End view of a high-speed marine engine

manufactured with 4, 6, or 8 cylinders and is of the conventional T-head type. In Fig. 111 may be seen a sectional view of one of the cylinders during the intake stroke, showing the valve

arrangement, the two camshafts, the relative position of the cams, etc. The valves are opened and closed at proper intervals by push rods actuated by the camshafts below.

Carburetion is secured by a carburetor of the type shown in section in Fig. 20. The fuel is delivered to the carburetor under constant pressure of 2 pounds per square inch by a small fuel pump of the gear type located on the forward side of the motor, and driven from the camshaft.

Both the generator-battery and the high-tension magneto systems of ignition are used on this engine. A self-starter is also fitted, the current necessary for this being supplied by the storage battery which is a part of the generator-battery system.

A very efficient system of forced lubrication is used, the oil pressure ranging from a minimum of 5 pounds to a maximum of 10 pounds per square inch. The oil is automatically and adequately cooled by being forced through a water-cooled oil cooler by means of a separate pump of the rotary-vane type.

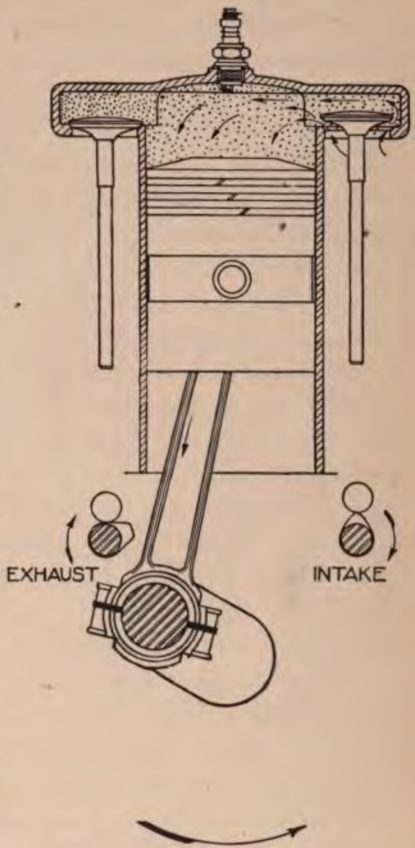


FIG. 111. Sectional view of cylinder for a high-speed marine engine, showing valve arrangement

The positive water-cooling of the engine secured by the use of the rotary-vane type of pump forces the water through the oil cooler and then around the cylinder walls, exhaust-valve

chambers, and spark-plug bosses and then out to the exhaust manifold, or directly overboard.

The engine described above runs at a speed of from 1000 to 1500 revolutions per minute and is used, both in the navy and commercially, for fast motor boats.

A Large Type of Gasoline Engine

Each of the 110-foot submarine chasers used by the United States navy was furnished with three large internal-combustion engines, each being a 6-cylinder, water-cooled, single-acting, 4-cycle engine having a cylinder bore of 10 inches and a stroke of 11 inches. These engines use gasoline for fuel and develop about 220 horse power each at 463 revolutions per minute. They cannot be started by hand. Starting is accomplished by taking compressed air at a pressure of 250 pounds into the cylinder on the working stroke through a valve actuated by a cam. The complete valve control of the engine, when starting with air as well as when operating on the gasoline mixture, is accomplished by means of a camshaft carrying several different complete sets of cams. There is one set of cams for running ahead and one for running astern.

These different cams automatically operate the air inlet and exhaust valves, and are thrown into operation for reverse or forward motion through a simple fore-and-aft movement of the camshaft. The compressed air for starting is furnished from an air-storage tank which is filled by an air compressor. The air compressor is mounted on the after end of the engine and is worked by an eccentric directly off the engine crankshaft. In case of emergency, the compressed air may be furnished by an auxiliary engine which is provided for this purpose. This engine is also used for pumping out bilges, pumping for fire purposes, and furnishing electric current for general use throughout the boat. The auxiliary engine is a 2-cylinder, 4-cycle engine having a cylinder bore of 4.5 inches and a stroke of 5.5 inches. An ordinary carburetor and a high-tension magneto are used on this auxiliary engine. It can be readily started by hand.

On the main engines a large vaporizer, instead of a carburetor, is used. This vaporizer automatically regulates the mixture of gasoline and air at all speeds. Gasoline is supplied to the vaporizer by a small fuel pump. The vaporizer and vertical intake pipe are water-jacketed, and warm water from

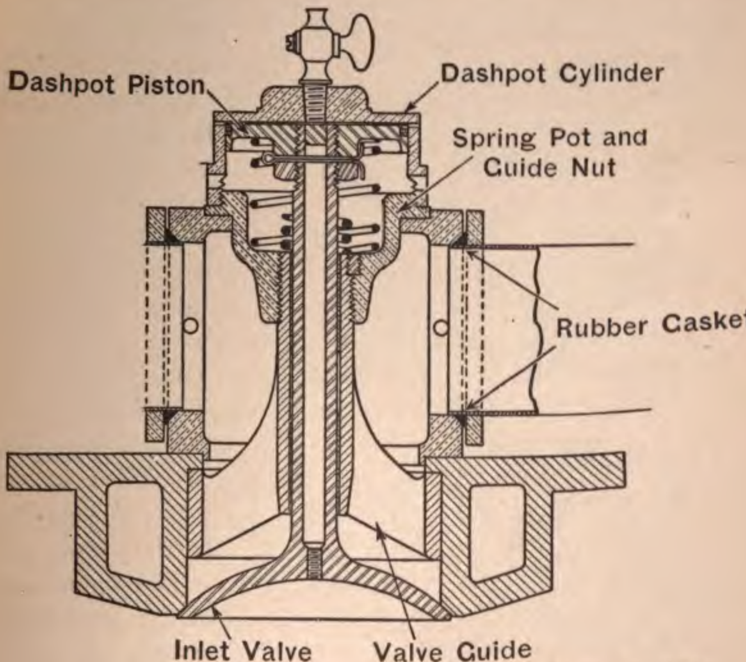


FIG. 112. Inlet valve assembly for a large gasoline engine

the cylinder heads, exhaust valves, and air compressor is circulated through these jackets by the customary circulating pump.

The inlet valve, shown in Fig. 112, is located in the cylinder head and is unusual because it is operated automatically by the vacuum created in the cylinder from the intake stroke of the piston. It is a steel mushroom valve fitted with a long, hollow stem for lightness. A brass cap containing a valve dashpot is screwed to the top of the valve bonnet. In this dashpot are a piston and spring which have a cushioning effect on the valve.

The exhaust valve is set to one side of the cylinder. It is mechanically operated by a pull rod actuated by the exhaust valve cam on the engine camshaft, which is correctly timed for proper opening of the valve on both running ahead and running astern. The valve, which is shown in Fig. 113, is of cast iron and so designed that it is balanced against the cylinder pressures. It is cast hollow its entire length. The stem is of hollow Monel metal and is screwed into the valve. This valve is water cooled by sending water from the cylinder jackets through it. The circulation of the water is indicated by the arrows.

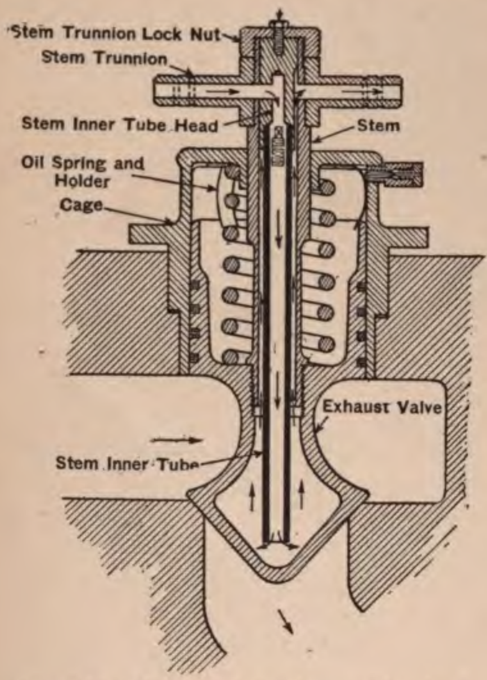


FIG. 113. Water-cooled exhaust valve for a large engine

The ignition is of the low-tension system. A simple low-tension magneto and a battery are used. The battery must be used for starting and for running astern. The magneto is used for running ahead. The ignition is of the make-and-break type, the ignition parts being operated by the igniter cam, which is set to fire the cylinders at the proper point.

Lubrication is supplied by a mechanical force-feed sight-feed lubricator which supplies oil to the various moving parts. There is no inclosed crankcase on this engine, so that hand lubrication may be used to supplement the regular lubrication system if required.

The piston for the engine is made of cast iron. The piston and wristpin are shown in section in Fig. 114. The piston has six piston-ring grooves, five above the wristpin and one below. The upper groove contains a single ring of cast iron, ground concentrically. All other grooves have four rings each. There are also three oil grooves, one above and two below the wristpin. The piston is ribbed for strength, and cast with radiation points on the underside of the head for cooling.

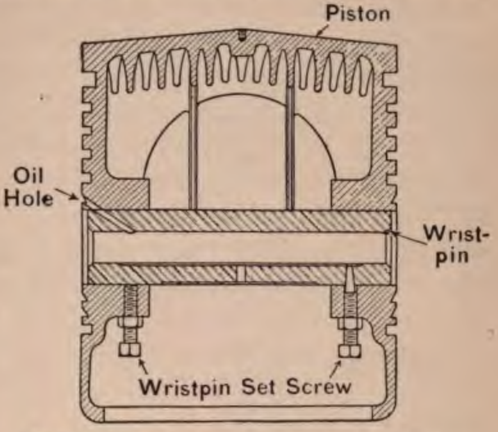


FIG. 114. Piston and wristpin for a large gasoline engine

The cylinders are made of cast iron. They are cast individually and have separate cast-iron cylinder heads. Both the heads and the cylinders are provided with ample water-jacketed spaces for cooling.

The designed speed for the submarine chasers at 463 revolutions per minute, using all three engines, is 18.75 knots.

HEAVY-OIL ENGINES

Heavy-oil engines of the Diesel type are used for the motive power of submarines and of many cargo and fuel ships. During the last few years an increasingly large number of cargo vessels have been equipped with heavy-oil engines of both the 2-stroke and 4-stroke cycle type. The 4-stroke cycle engine seems to be preferred for commercial vessels. In submarines both the 2-cycle and 4-cycle engines are used. The 2-cycle Diesel engine, though a trifle less efficient than the 4-cycle, possesses the valuable advantage of easy reversal. It is also of lighter weight and requires less space for a given horse power than the 4-cycle.

The horse power of the Diesel, or constant-pressure, type of engine is somewhat limited by practical considerations in construction. At the present time the satisfactory maximum power attainable is from 300 to 400 horse power per cylinder. Some single-acting experimental engines have been built abroad recently which developed over 1000 horse power per cylinder.

In Fig. 115 is shown in section one cylinder of a Diesel engine with a 2-stage air compressor driven directly from the crankshaft. In this engine the inlet and exhaust valves and the fuel-injection valve are located in the cylinder head. The exhaust valve must be water-cooled. The most important advantage of using a Diesel engine is that of fuel economy, which gives increased radius of action. In the case of submarines the advantage of increased safety due to the type of fuel used is of great importance, as is also the absence of smoke in this type of war vessel.

For small powers heavy-oil engines of the so-called semi-Diesel type are used. The compression used in these engines is only about one half that used in the Diesel engine, and as this degree of compression does not provide enough heat to ignite the fuel, a cast-iron bulb is fitted in the head of the cylinder. It is necessary to heat this bulb before starting the engine. This is done by directing against it for a few minutes the flame of a blow lamp. After the engine is started, the heat of combustion maintains the bulb at a temperature sufficient to vaporize and ignite the fuel which comes in contact with it.

Automobile Engines

Before the World War the automobile industry was responsible for the development and refinement of the internal-combustion engine using gasoline for fuel. During the war this refinement was carried to its present high state by the manufacturers of aircraft engines. As automobiles are intended to be operated by persons more or less unfamiliar with internal-combustion engines, they must be designed with a view to simplicity, in order that the power plant may receive the proper care from

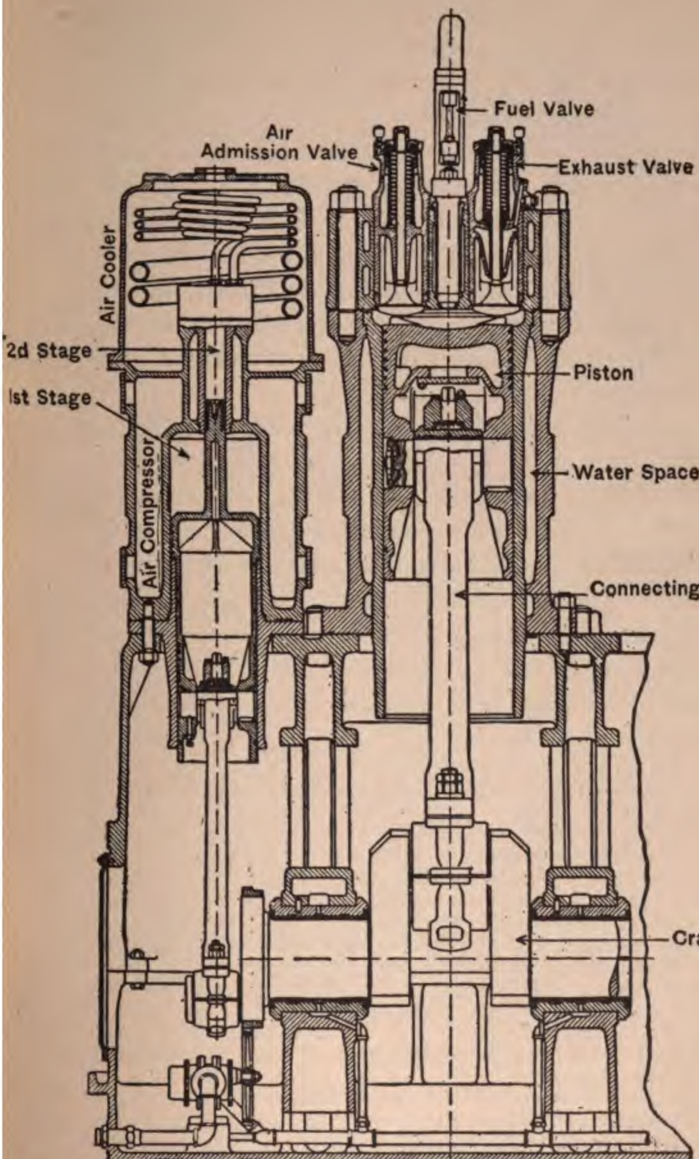


FIG. 115. Section of Diesel engine showing one cylinder and a 2-stage air compressor directly connected to crankshaft

operators who are, for the most part, mechanically inexperienced. The requirements of all forms of automobile engines are practically the same. They must be light, compact, flexible, of high power, and almost noiseless.

Previous to 1914 automobiles were equipped with 4-cylinder or 6-cylinder vertical engines. In 1915 the 8-cylinder and 12-cylinder V-type motors first made their appearance in American automobiles, although this type of engine had been used for many years as the power plant for aëroplanes. The multiplication of the number of cylinders, in addition to the gain in power, gives a more uniform turning movement, greater flexibility, and decreased vibration.

In Fig. 116 is shown complete a representative 12-cylinder power plant, and in Fig. 117 is shown a front view, part in section, of the same engine. It will be noted that this engine employs the L-head arrangement of valves and uses but one camshaft. The cylinders are cast in blocks consisting of 6 cylinders each. The left cylinder block is set $1\frac{1}{4}$ inches ahead of the right block to permit the lower end of the connecting-rod bearings from opposite cylinders to be placed side by side on the same crankpin. The cylinder heads are removable. The

Description of Illustration on Opposite Page (Fig. 116)

1, motor fan; 2, distributor bearing oiler; 3, distributor; 4, distributor spiral gear oiler; 5, motor-cylinder petcock; 6, ignition spark-plug assembly; 7, motor-cylinder inlet manifold gasket; 8, motor-cylinder inlet manifold stud nut; 9, motor-cylinder inlet manifold; 10, motor-cylinder head stud nut; 11, ignition high-tension cable tube, left, assembly; 12, motor-cylinder water-jacket plate; 13, exhaust manifold, left; 14, exhaust manifold, right; 15, ignition high-tension cable tube, right, assembly; 16, clutch pedal pad; 17, foot-brake pedal pad; 18, motor-starter switch; 19, clutch and brake pedal oiler; 20, clutch cover; 21, tire pump; 22, transmission-case oil-filler plug; 23, transmission gear-shifter interlocking plunger retainer; 24, transmission driveshaft rear-bearing housing; 25, speedometer-driven gearshaft bearing; 26, transmission driveshaft universal joint shaft flange; 27, transmission reversing pinion pin; 28, tire-pump gear-shifter lever retracting spring; 29, tire-pump case-end cap; 30, clutch-shifter lever connecting yoke end adjusting wing nut; 31, clutch-shifter end bearing oiler; 32, clutch-shifter lever; 33, clutch-shifter lever connecting yoke end, adjusting spring; 34, clutch-shifter lever connecting yoke end, adjusting; 35, foot-brake pedal; 36, clutch pedal; 37, motor oil-pump; 38, exhaust manifold extension; 39, motor crankcase, lower half; 40, motor-cylinder water inlet manifold, left; 41, motor crankcase overflow valve assembly; 42, motor crankcase overflow valve handle; 43, motor crankcase oil filler assembly; 44, motor fan-belt

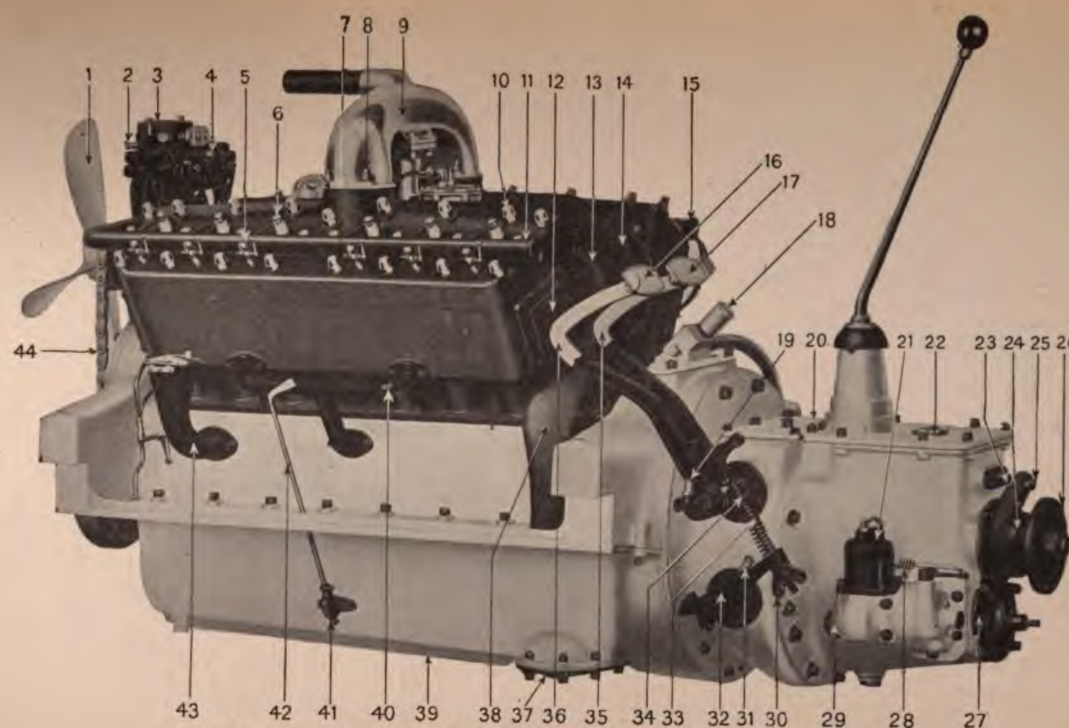


FIG. 116. A representative 12-cylinder automobile power plant complete

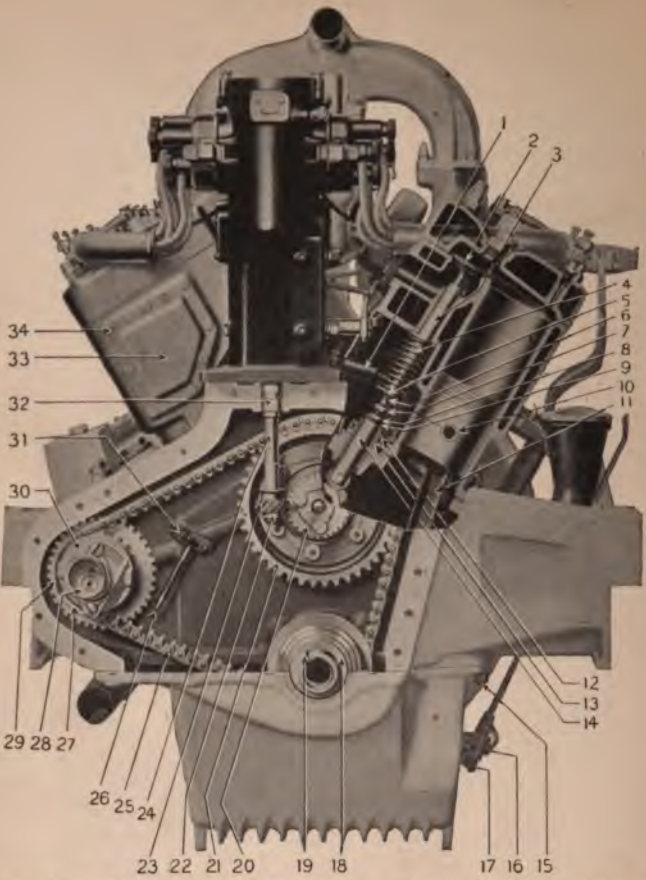


FIG. 117. View showing construction of a 12-cylinder automobile engine

1, motor-valve cover stud-nut assembly; 2, motor valve, exhaust; 3, motor-valve stem guide; 4, motor-valve spring; 5, motor-valve spring collar; 6, motor-valve spring collar key; 7, motor-valve roller holder screw; 8, motor-valve roller holder screw check nut; 9, motor-valve roller holder screw plate; 10, motor piston-pin; 11, motor connecting-rod; 12, motor-valve roller holder guide yoke; 13, motor-valve roller holder guide; 14, motor-valve roller holder and roller assembly; 15, motor crankcase upper to lower stud nut; 16, motor crankcase overflow valve stud nut; 17, motor crankcase overflow valve spring; 18, motor crankshaft oil thrower; 19, motor fan driving pulley key; 20, motor camshaft spiral gear, front; 21, motor camshaft sprocket; 22, distributor driveshaft nut; 23, distributor driveshaft gear; 24, distributor driveshaft; 25, motor camshaft driving chain; 26, motor camshaft drivechain oil tube assembly; 27, gasoline power-pressure pump eccentric lock; 28, gasoline power-pressure pump eccentric; 29, motor-generator sprocket eccentric; 30, motor-generator sprocket coupling, female; 31 motor camshaft driving chain oil tube flange nut; 32, distributor driveshaft bushing, upper; 33, motor-cylinder water-jacket plate; 34, motor-cylinder water-jacket plate screw

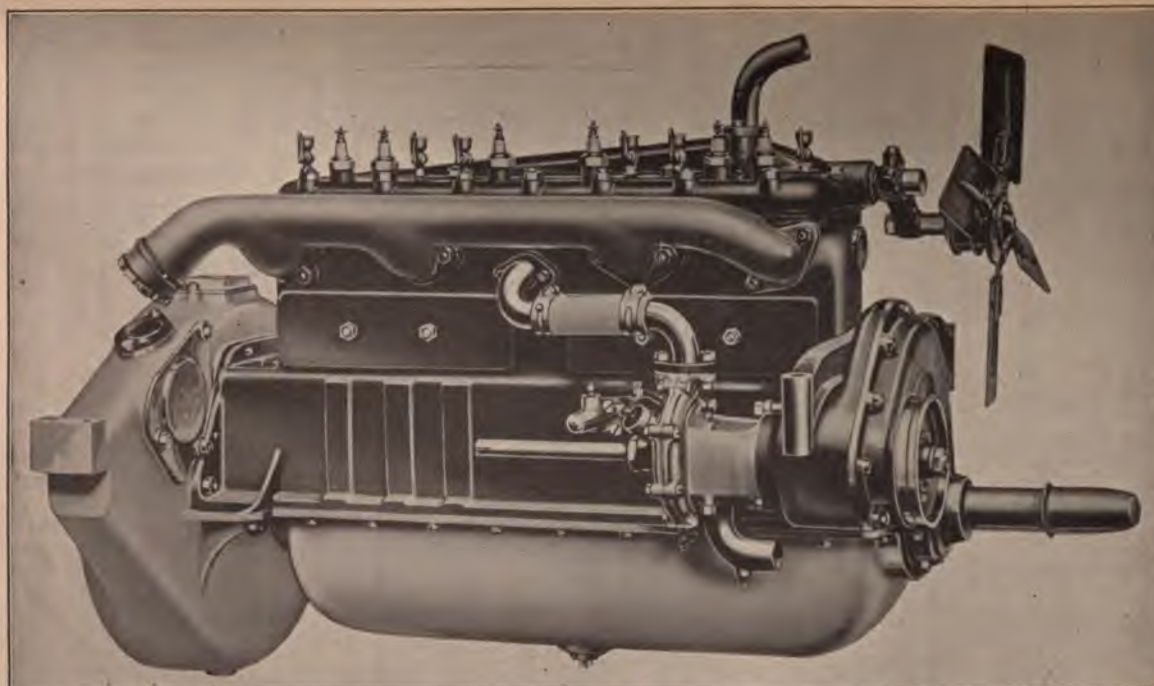


Fig. 118. Six-cylinder automobile engine complete. This type of engine is used on many American cars

pistons are of aluminum. The cylinder bore is 3 inches and the stroke 5 inches. Force-feed lubrication is used.

A vertical type of 6-cylinder motor used in many automobiles is shown complete in Fig. 118. In Fig. 119 is shown a sectional view of the same engine. The cylinder block and upper half of the crankcase are one iron casting. The cylinder head is removable, permitting easy access to valves and combustion chambers. The pistons are of cast iron. A combination of the splash and force-feed system of lubrication is used in this engine.

Choice of Ignition Systems for Automobile Engines as effected by the Use of a Self-Starter

A self-starting system is now furnished on most modern automobiles. This consists of a small electric motor which is mechanically connected to the engine, usually through the flywheel, and electrically connected to a storage battery which furnishes the current required for starting. The battery is kept charged by a small generator, which also furnishes the current for lighting.

Ignition systems for automobile engines may be by the generator-battery or by high-tension magneto. The former preceded the latter in the early stages of automobile development, then disappeared almost completely, giving way to the magneto. The introduction of the *self-starter*, however, with its necessary accessories—the generator and the storage battery—has resulted in the perfection of generator-battery ignition to a high degree, so that it is now found on many cars. Magneto ignition is somewhat simpler, because one instrument performs the functions of the battery, distributor, and generator of the generator-battery system. The magneto does not, however, store up electricity available for use in connection with the self-starter; and hence, if an electric self-starter is to be used on an engine fitted with high-tension magneto ignition, a separate generator and a separate storage battery must be provided.

The Vacuum System of Fuel Feed

Of late years there has been a tendency on the part of automobile manufacturers to adopt the vacuum fuel-feed system to draw gasoline from the main tanks, which may be located below

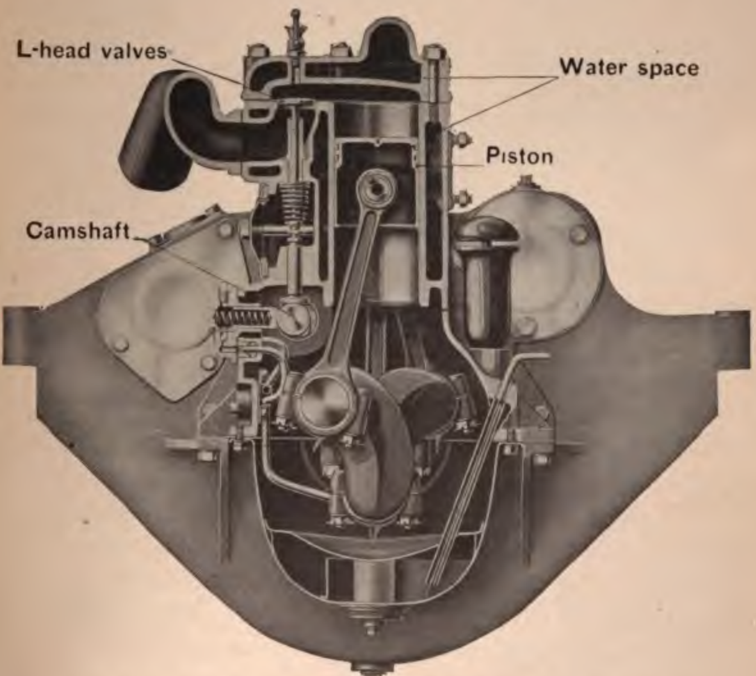


Fig. 119. Front view showing construction of a 6-cylinder automobile engine

the level of the carburetor, instead of using either the pressure from the exhaust or independent air pressure to achieve this end. The device generally fitted is the vacuum feed tank, which is shown in section in Fig. 120. In this system the suction of the motor is employed to draw gasoline from the main fuel tank to the auxiliary tank incorporated in the device. From this tank the liquid flows to the carburetor. It is claimed that all the advantages of the pressure system are obtained from this vacuum

system with very little more complication than is found in the ordinary gravity feed system which is still widely used.

The mechanism is all contained in the cylindrical tank shown, which may be mounted either on the front of the dash

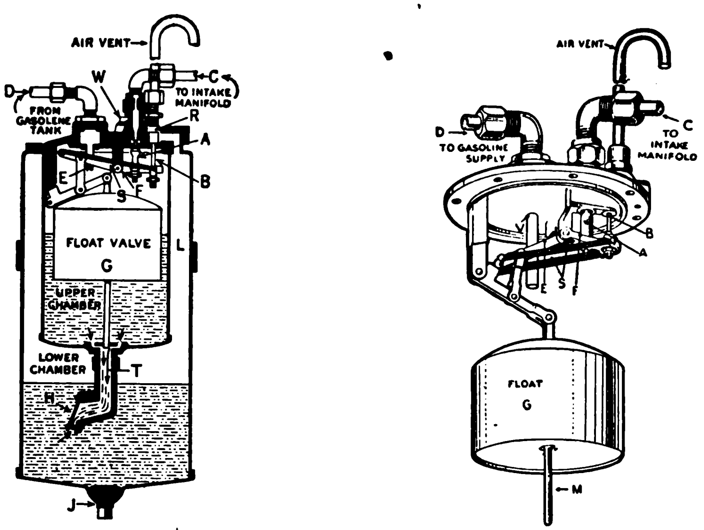


FIG. 120. Sectional view of the vacuum feed tank used on many automobiles

A, suction valve; *B*, atmospheric valve; *C*, pipe to suction yoke; *D*, pipe to main tank; *E*, valve lever (long); *F*, valve lever (short); *G*, float; *H*, flapper valve; *J*, pipe to carburetor; *L*, air passage; *M*, float guide; *R*, air vent; *S*, valve springs; *T*, flapper valve housing; *W*, priming plug

or on the engine above the carburetor, wherever it is most convenient. The upper or filling chamber of the tank contains the float valve, as well as the pipes running to the main fuel container and to the intake manifold. The pumping action of the pistons during the intake stroke of the engine creates the vacuum in the upper chamber. This vacuum sucks the gasoline from the main supply tank and the float valve action permits it to flow into the lower chamber. This lower or emptying chamber is used to supply the carburetor with gasoline and, by virtue of the air vent shown, is under atmospheric pressure at all times, so that the flow of fuel from it is by means of gravity only.

CHAPTER XVI

TROUBLES: CAUSE, EFFECT, AND REMEDY

When the Engine refuses to Start

A refusal to start can, in nine times out of ten, be traced to an open switch or no gasoline. In this case do the simplest things first, — see if the switch is turned on and then examine the fuel supply.

If it is cold weather and the engine has been stopped long, it will naturally be harder to start. If, after several turns of the crankshaft, no results are obtained, prime each cylinder with a teaspoonful of gasoline through the pet cocks or priming cups provided for that purpose.

If the motor still refuses to start, test the ignition current by grounding each spark plug separately while the motor is being turned over. The shank of a screwdriver held against the spark-plug terminal and the point held within a sixteenth or a thirty-second of an inch of any part of the cylinder will reveal a spark between the gap if the current is being properly distributed. Do not touch any metal portion of the screwdriver when making this test or a shock will result. The same result can be accomplished by disconnecting the wire from the spark plug and holding the wire terminal near the spark-plug terminal. If no spark occurs at any of the terminals, the fault is in the ignition system.

If, after priming the cylinders as described above, the engine turns over a few times and then stops, it is an indication that the ignition is all right but that the motor is either getting too much fuel or none at all. Examine the carburetor, and if it is flooding, drain it by means of a pet cock usually provided for

that purpose. Sediment in the gasoline will sometimes clog up the carburetor spray nozzle and cut off the fuel, or the fuel line may freeze up in extremely cold weather if the fuel contains any water. The remedies for these difficulties are obvious. Gasoline should be thoroughly filtered before being put into the tank. The filtering material will stop all dirt and water, while permitting the gasoline to drain through.

When Engine refuses to Stop

This is usually due to a short circuit in the switch or a disconnected ground wire. If the motor is overheated, combustion may take place without the presence of a spark, and the engine will continue to run erratically. If all efforts fail to stop the engine, it may be stalled by throwing on a heavy load or by applying the brakes.

When Engine stops without Warning

This may be due to lack of fuel or to a disconnected or broken wire on the ignition system. If, after these two things have been investigated and found in good order, the engine still fails to start, try the three following tests: (1) Turn the motor over with the hand crank. If it is extremely difficult or impossible to crank the engine, the natural supposition is that there is a seized bearing or piston, due to the lack of oil or water. Allow the engine to cool, fill the oil reservoir or radiator, as the case may require, and then try starting the engine again. (2) Try the priming test, to determine whether or not the carburetor or gasoline line is clogged. (3) Test the ignition system as described above. If the car is equipped with the generator-battery system of ignition, the trouble may be caused by an exhausted battery. If no ammeter is provided with the engine, apply to the battery terminals the screwdriver test already described, to see if a spark can be secured therefrom. The battery is one of the most sensitive parts of an ignition system and if neglected will quickly depreciate and cause trouble.

When the Engine misses Fire

To locate the missing cylinder, open each pet cock or priming cup separately while the motor is running at fairly good speed. A blue flame, accompanied by a sharp report, will indicate the cylinders which are firing properly.

Missing of the power stroke may be caused by several defects, of which the following are the most important: (1) improper adjustment of carburetor; (2) defective spark plugs,—a cracked porcelain, too wide a gap between the points, or sooted points; (3) a broken or disconnected wire; (4) dirt in the carburetor; (5) loss of cylinder compression; (6) water in gasoline.

(1) The first item requires the attention of a person experienced in carburetor adjustment; (2) the second can be readily located and then remedied by the substitution of a new spark plug; (3) a broken or disconnected wire can nearly always be easily located and then repaired or replaced; (4) in case of dirt in the carburetor the instrument should be removed and, without disturbing the adjustment, thoroughly cleaned out; (5) loss of cylinder compression is due to worn piston rings, worn cylinders, or improperly seated valves (this requires the attention of a mechanic); (6) water in the gasoline can be detected by the fact that the engine will stop and start intermittently without apparent cause. The remedy for this has already been given.

Loss of Power

The simplest cause of loss of power is improper carburetor adjustment. The most serious cause is loss of compression. Others are carbonization, excessive heat, flooded carburetor, and lack of oil.

The remedies for most of these are obvious, but a word on the subject of loss of compression may be helpful. To detect this defect the engine should be turned over slowly with the starting crank. The cylinder having weak compression can be readily located by the lack of resistance offered at the crank by the advancing piston as compared with the resistance offered in the other cylinders. Look first for an improperly seated valve.

Carbonization

When a motor has been run for a long period without being cleaned out, or if an excessive amount of oil has been used, the interior of the combustion chambers and the top of the piston will become coated with carbonaceous matter. The longer the motor runs, the heavier this deposit becomes, until finally the volume of the combustion chamber is appreciably reduced and the compression is proportionately increased.

The result is that the motor quickly heats up and the inevitable consequences follow. A certain peculiar knock in the motor, accompanied by excessive heat, is conclusive evidence of the presence of carbon.

Overheating

We have already seen that carbonization will cause overheating. This, however, is not the cause which will be encountered most. Lack of water and oil are the most common causes. A late spark is another cause of overheating.

Freezing

If a jug is filled with water and allowed to freeze, the jug will burst. The same thing happens to a cylinder block unless the proper precautions are taken. As soon as the temperature approaches the freezing point the following or an equally efficient solution should be substituted for water in the radiator: glycerin 10 per cent, denatured alcohol 25 per cent, water 65 per cent. If the engine is to stand idle for a considerable length of time (for example, a month), the water should be drained off entirely from the radiators, cylinders, and water pump.

Knocks

A knock is a warning that something is wrong with the engine. The instant a knock is heard, its location and cause should be determined.

The common causes of knocks are carbon in cylinders, too rich a mixture, motor speed too low when pulling hard, loose bearings and loose valve tappets. Only experience will make one proficient in locating a knock. Each type has a different sound, and frequently a knock will appear to be at one end of the engine when the cause is actually at the other.

If the engine knocks when it is overheated, it is reasonable to suppose that there is carbon present — provided, however, the engine has a tendency to heat up rapidly. A knock caused by a rich mixture can readily be identified by testing different carburetor adjustments.

It is impossible to mistake the knock occasioned by too low a speed under heavy load. One can always tell when a motor is laboring, by this unmistakable protest. This knock takes the form of a ringing or clinking sound, occurring in rapid succession. The spark should be retarded, to relieve the engine as much as possible.

Loose bearings are the most difficult to identify and locate, for the sounds vary according to conditions. Usually, however, a knock on the main crankshaft bearing takes the form of a dull pounding or thumping, while that on a connecting-rod or wrist-pin bearing is sharp and higher in pitch.

A loose valve tappet is easily detected. This makes a light tapping noise or click. The valve tappets should be kept properly adjusted.

THE TROUBLE CHART

The following chart, based on American-built engines, has been prepared to outline in a simple manner the various troubles that interfere with the efficient action of gasoline engines.

A chart of this kind is intended merely as a guide, and it is a compilation of practically all the known troubles that may materialize in gasoline-engine operation.

TROUBLE CHART

Part at Fault	Trouble	How it Affects the Engine	Remedy
Spark Plugs	Oil deposit	Missing	Clean the plug. If this does not help, replace with new plug
	Carbon deposit	Missing	Clean the plug. If this does not help, replace with new plug
	Points too close	Missing or skipping	Reset to from .02″ to .03″
	Points too far apart	Missing or skipping	Reset to from .02″ to .03″
	Cracked insulator	Missing or skipping	Replace with new plug
	Leaking by threads in cylinder	Loss of compression	Screw plug tight in cylinder
	Leaking by insulator	Loss of compression; missing	Replace with new plug
Valves	Warped or pitted on seat	Loss of compression. If inlet valves, may blow back in carburetor	True up in lathe and grind to seat
	Burned on seat	Loss of compression	If not burned too badly, true up on lathe and grind to seat
	Too tight in guide	Miss and skip (blow-back in carburetor if inlet); loss of compression	Free valve with crocus cloth and then adjust for clearance; regrind
	Too loose in guide	Seat will not stay ground; miss and skip; loss of compression after running awhile	Renew valve if worn; if still too much clearance, renew guide and adjust clearance

TROUBLE CHART (CONTINUED)

PART AT FAULT	TROUBLE	HOW IT AFFECTS THE ENGINE	REMEDY
VALVES (Continued)	Carbon under seat	Missing; loss of compression	True up in lathe and regrind
	Closes late	Engine misses and loses power	Check clearance on back of cams and valve tappets; re-time camshafts
	Opens early	Engine misses and loses power	Check clearance on back of cams and valve tappets; re-time camshafts
	Closes early	Engine misses and loses power	Check clearance on back of cams and valve tappets; re-time camshafts
	Opens late	Engine misses and loses power	Check clearance on back of cams and valve tappets; re-time camshafts
MAGNETOS	Dirty distributors	Missing or skipping	Clean out any carbon deposit and give a thin coating of good oil
	Breaker points not correctly adjusted	Missing or skipping	Adjust to .020″
	Broken-down condenser	Missing; sparking and burning of platinum points	Replace with new condenser
	Loose or broken wire in distributor block	Misses on that particular cylinder	Tighten or renew wire if broken
	Collector brush on armature broken or dirty	Missing	Renew if broken; clean if dirty

TROUBLE CHART (CONTINUED)

PART AT FAULT	TROUBLE	HOW IT AFFECTS THE ENGINE	REMEDY
MAGNETOS (Continued)	Armature shaft broken	Magneto or generator will not work; loss in power	Replace with new magneto or generator
	Punctured or burned-out coil	Missing	Replace with new coil
CARBURETORS	Lean mixture	Back-fire in air inlet of carburetor	Enrich the mixture by means of control adjustment
	Rich mixture	Engine runs unevenly	Weaken the mixture
	Engine runs unevenly when it is idling		Regulate the idling adjustment so as to weaken the mixture
	Engine back-fires when idling		Regulate the idling adjustment to enrich the mixture
PISTONS AND PISTON RINGS	Piston walls scored	Poor compression; loss of power	Replace with new rings
	Piston rings scored	Loss of power	Replace with new rings
	Worn or broken rings	Loss of power	Replace with new rings
	Loss of spring in piston rings	Loss of power; oil working into combustion chamber	Replace with new rings
	Rings loose in grooves	Oil works by rings into combustion chamber	Fit new pistons or use oversize-width rings
TIMING	*Valves:* Camshaft not properly timed	Loss of power and back-firing in carburetor	Correct timing of camshafts

TROUBLE CHART (CONTINUED)

PART AT FAULT	TROUBLE	HOW IT AFFECTS THE ENGINE	REMEDY
TIMING (Continued)	Insufficient clearance between cams and valve tappets	Loss of power; varies the point of opening and closing of valves	Set clearance to about .01″
	Distributor: Too much advance	Loss of power; preignition	Retard to fire later
	Insufficient advance	Loss of power; engine overheats	Advance to fire earlier
OIL PUMP AND LUBRICATION	Insufficient oil	Oil pressure drops	Replenish oil supply
	Poor quality of oil	Loss of power	Renew with good grade of oil
	Dirt in oil	Burned-out bearings	Dismantle engine and renew bearings
	Pressure drops at times		Examine oil pump and see if oil is clean
	Excessive oil pressure		Oil relief valve stuck; remove valve and examine; oil may be cold
WATER CIRCULATION SYSTEM	Water does not circulate	Loss of power; water boiling	Water-pump shafts or impeller may be broken. Replace; clean water system
MAIN BEARINGS	Babbitt or white metal burned out	Knocking; loss of power; drop in oil pressure	Replace with new bearing
CONNECTING-ROD AND BEARINGS	Babbitt or white metal burned out	Knocking; loss of power; drop in oil pressure	Replace with new bearing
	Bolts on connecting rods break	Knocking; loss of power	Replace with new bolts and repair other damage

TROUBLE CHART (Continued)

Part at Fault	Trouble	How it Affects the Engine	Remedy
Cylinders and Water Jacket	Scored wall	Knocking	Smooth up, or replace with new cylinder
	Water leak in jacket	Will not hold water	Repair leak, or replace with new cylinder
	Jacket covered with scale or dirt	Knock caused by overheating	Dissolve scale and flush out water space with water under pressure
Timing Gears or Camshaft Drive	Worn or broken teeth, or teeth meshed too deeply	Metallic knock or rattle; grinding	Replace with new gears; mesh properly; regrind
	Loose gears	Metallic knock	Fasten gears to shaft

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